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The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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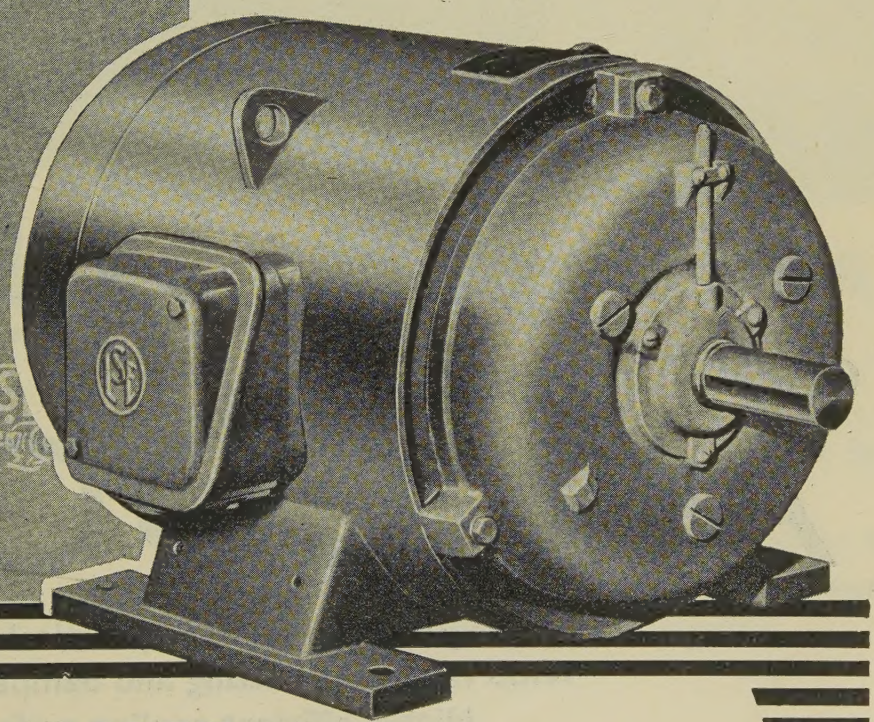
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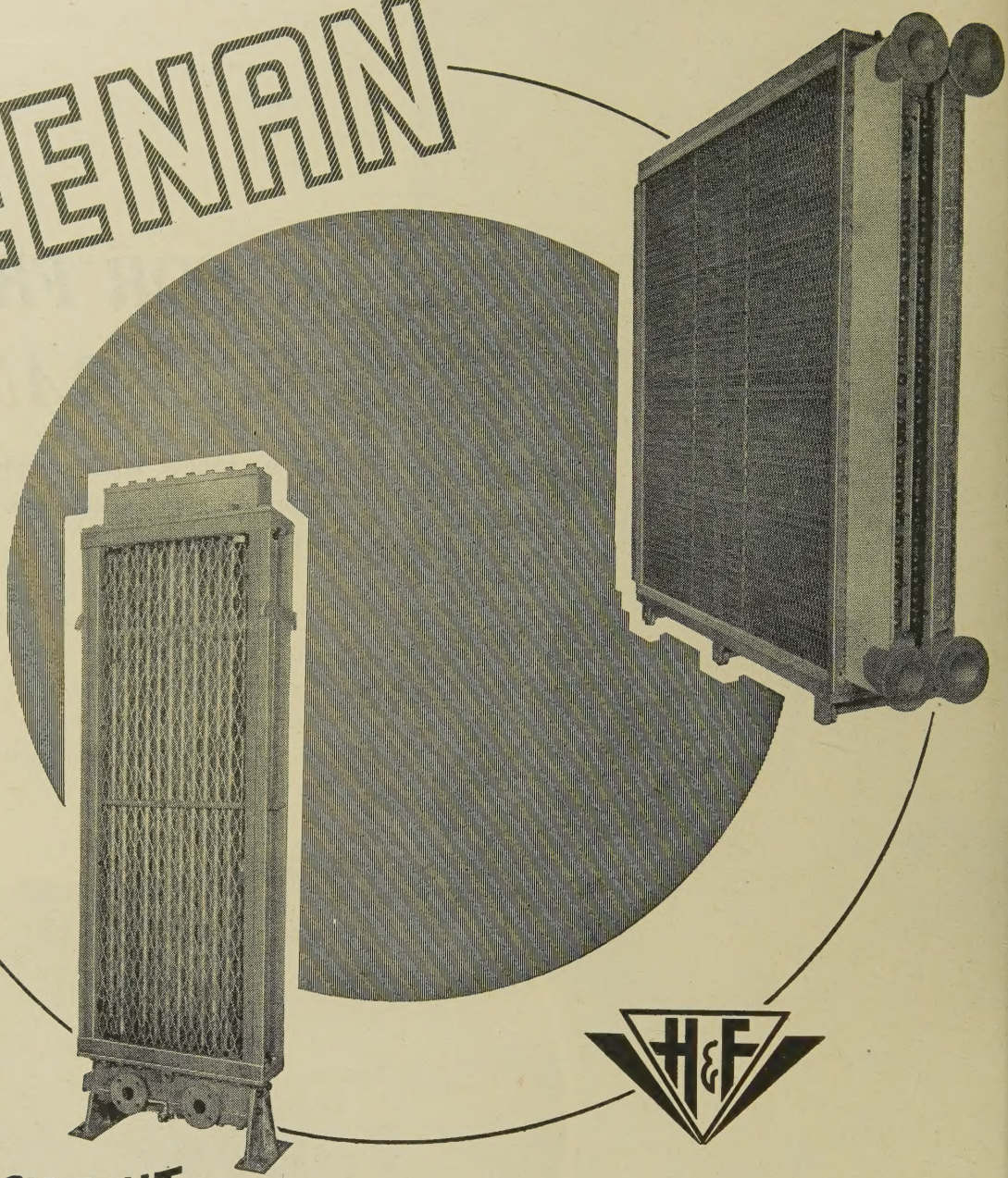


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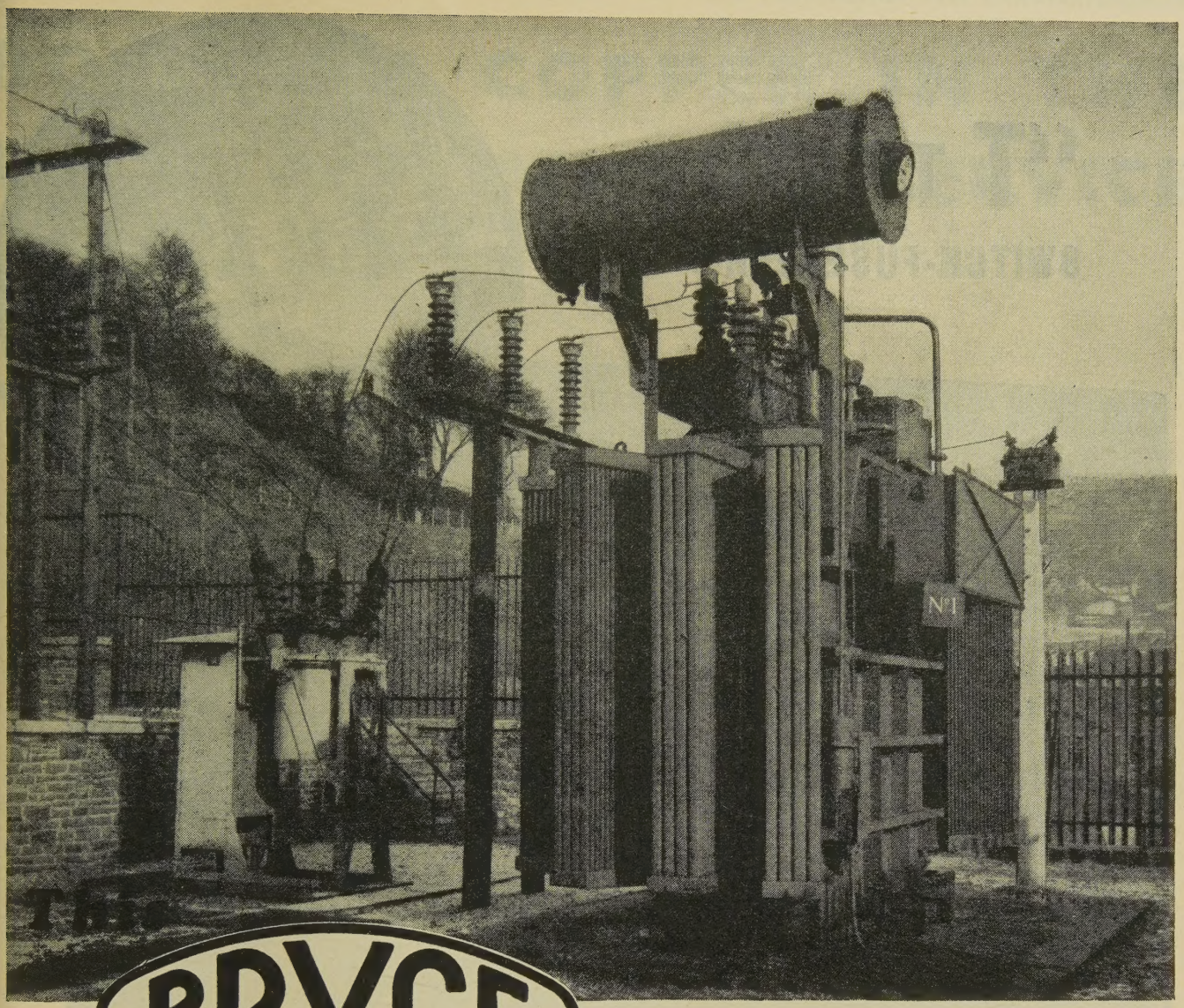
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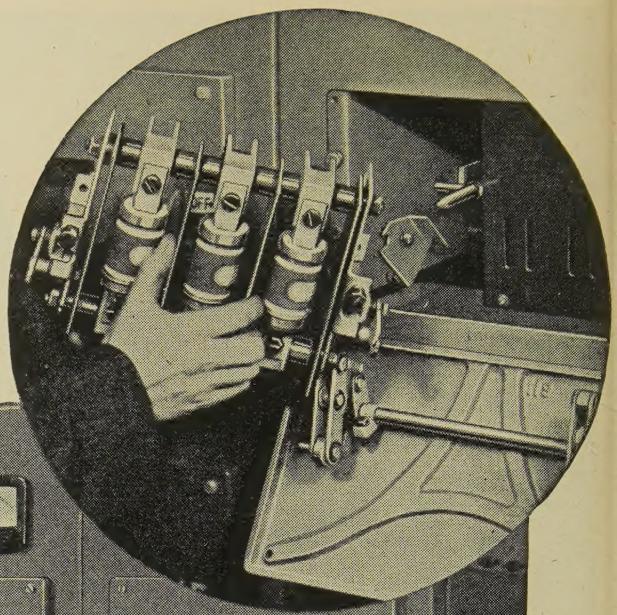
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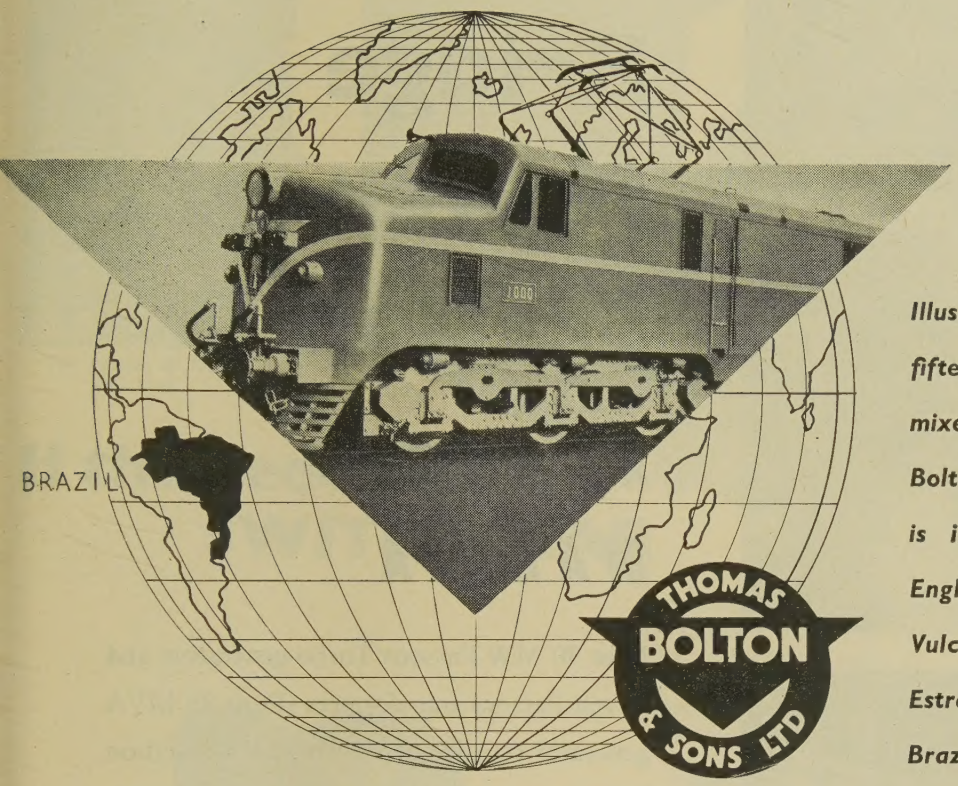


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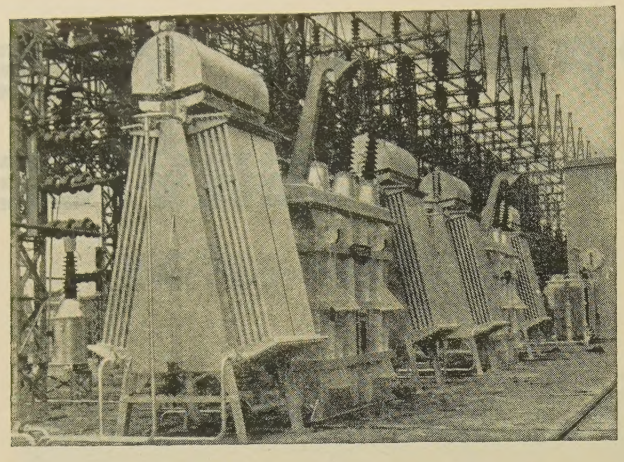
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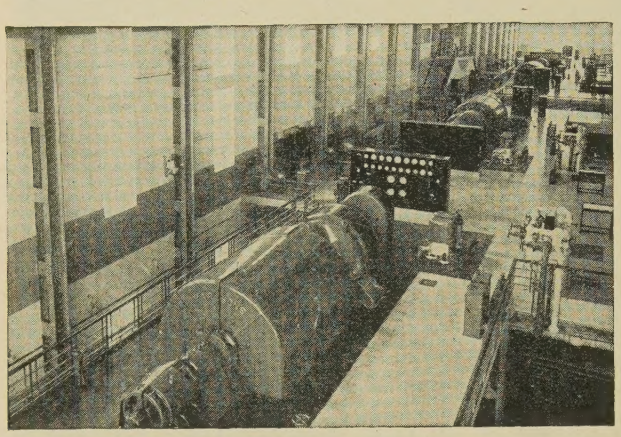
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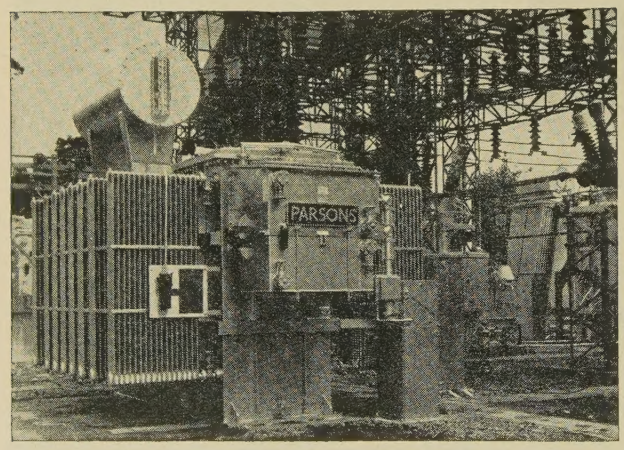
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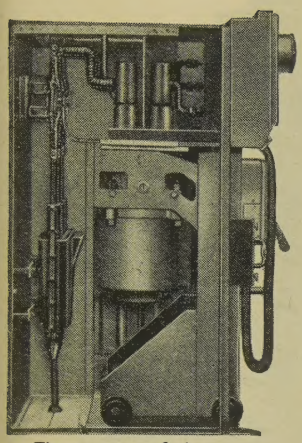
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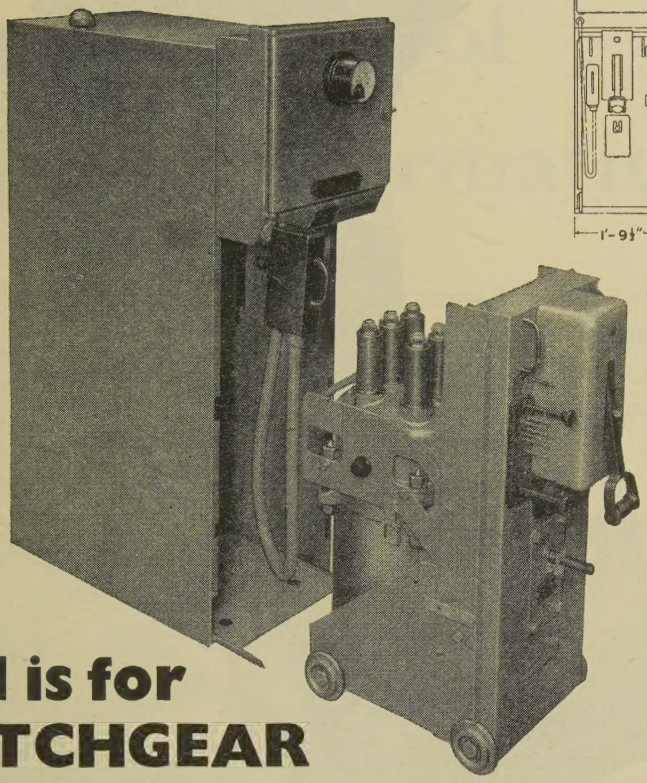
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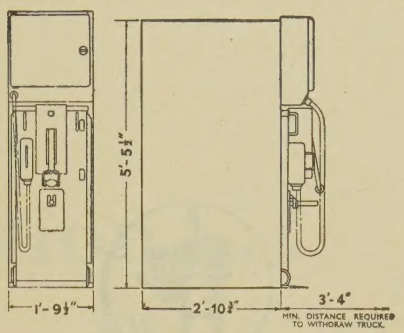
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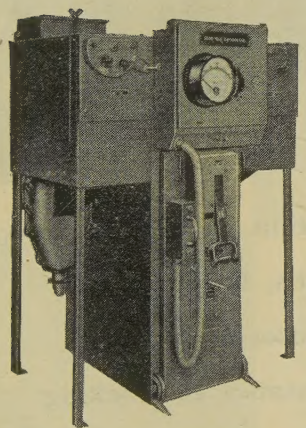
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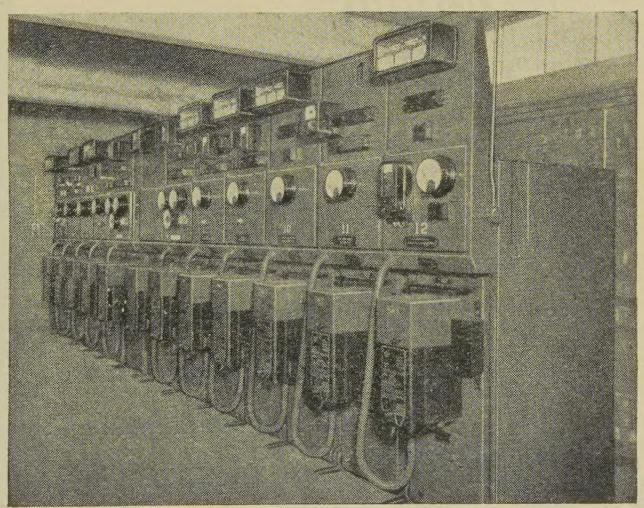
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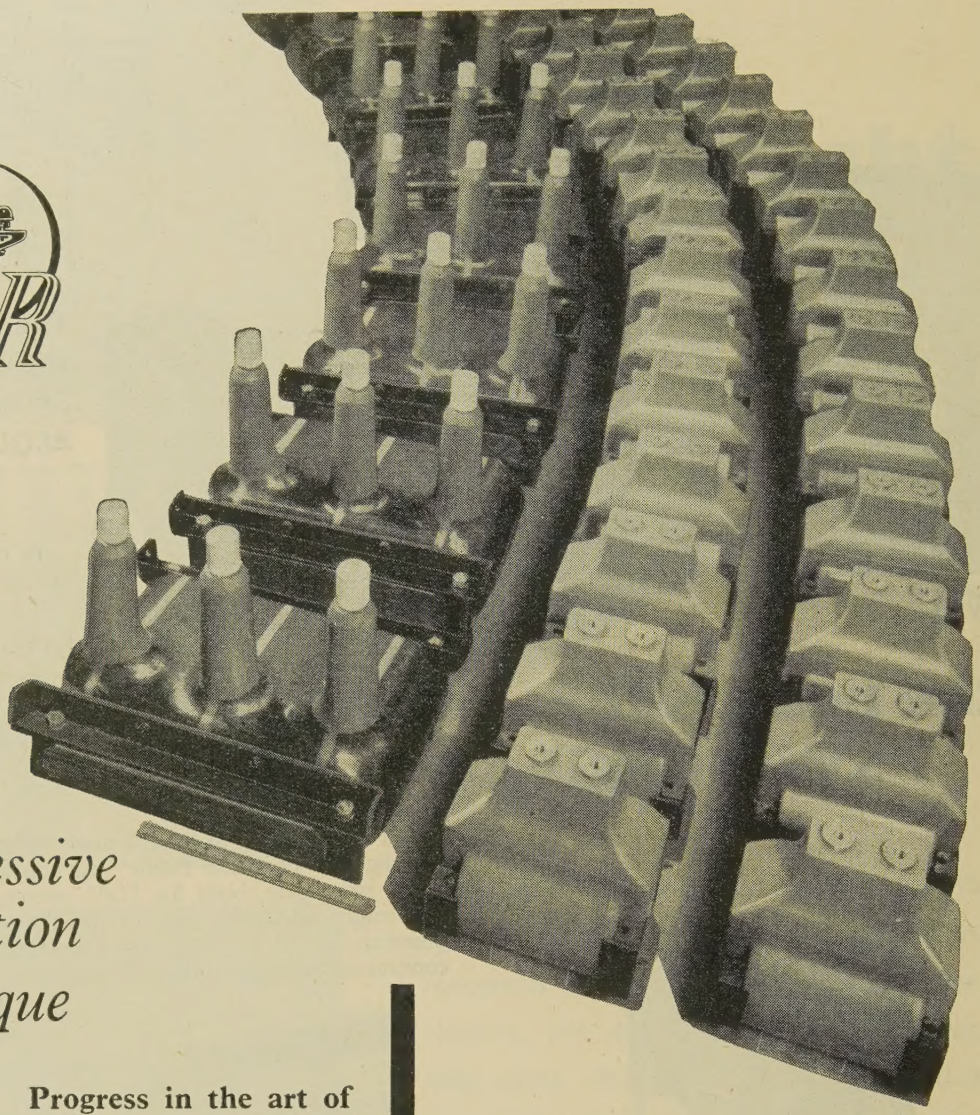
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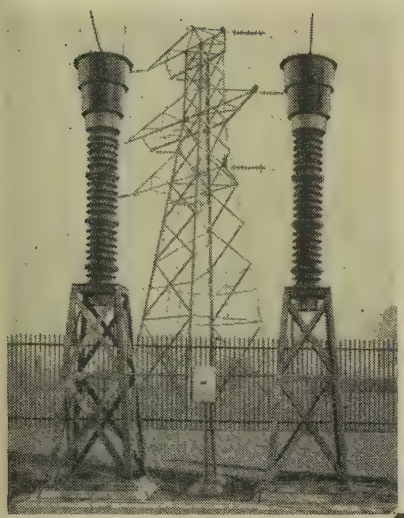
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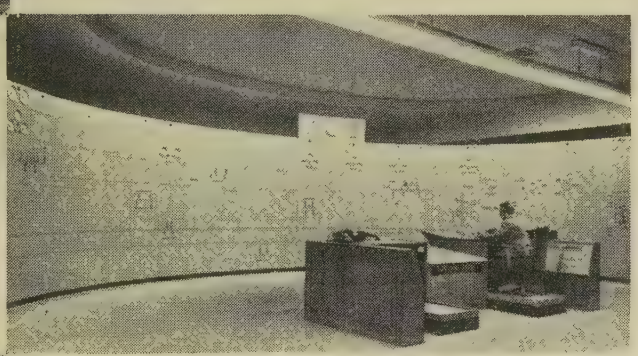
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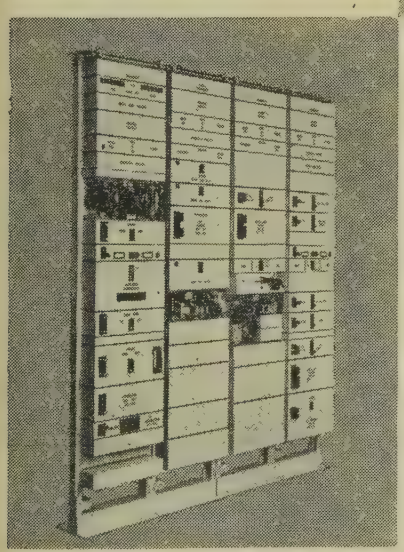
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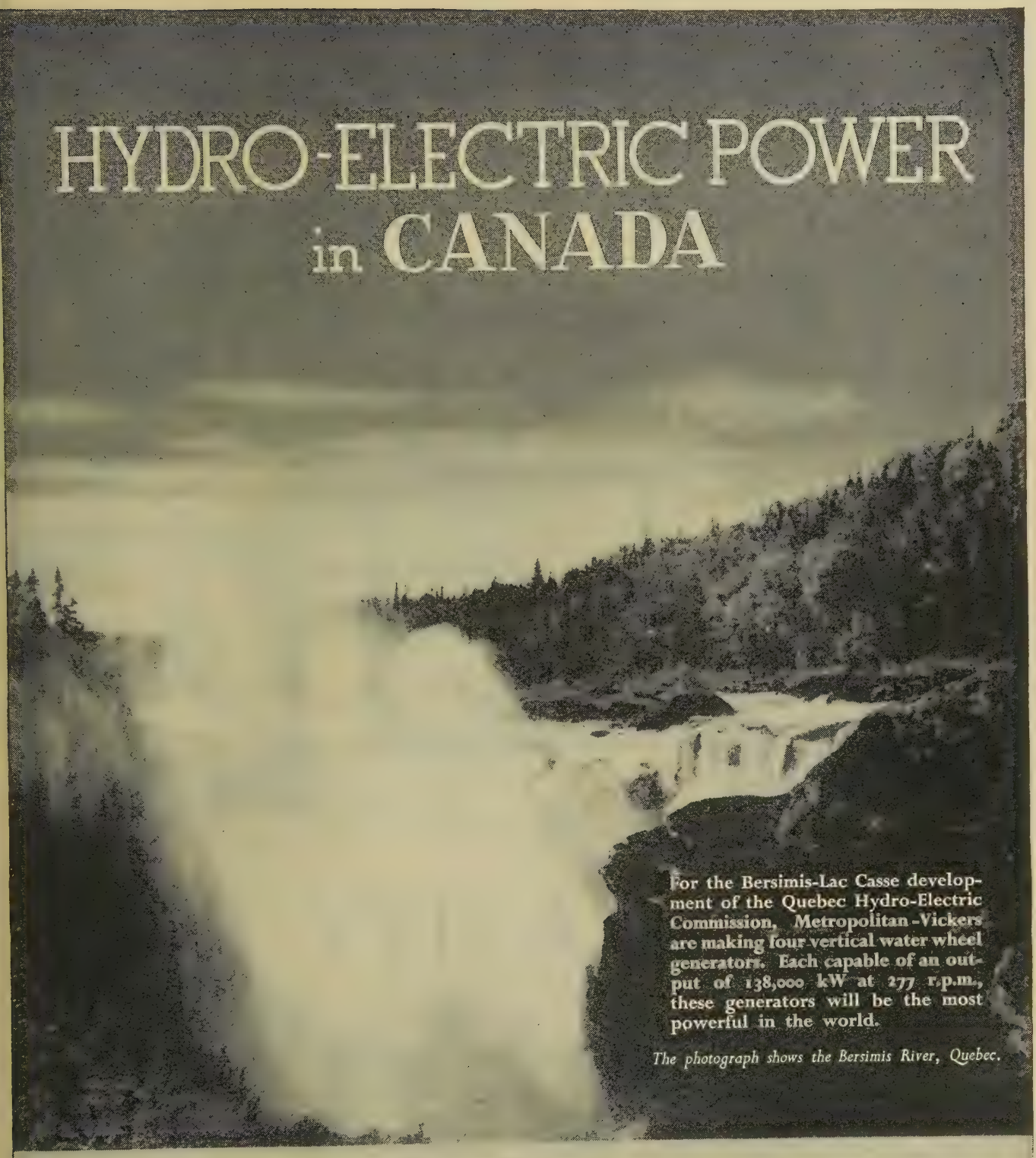
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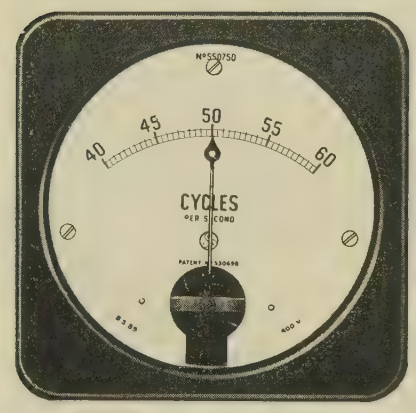
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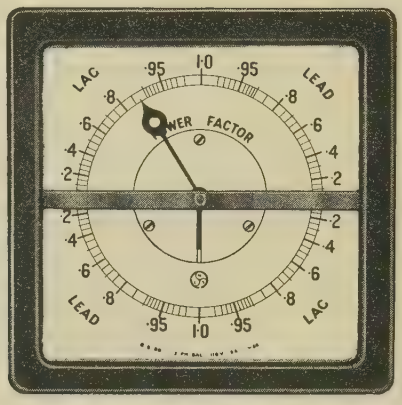
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The 'Roman Warrior' and the 'C.M.A.' trademarks are symbols of the highest quality standard in electric cable manufacture — recognized throughout the world. Over one million pounds spent each year on research and development by member companies, together with constant testing to maintain the high C.M.A. standards, ensure that 'C.M.A.' will be engraved still deeper on the industrial life of the world.

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Insist on a cable with the C·M·A label

The Roman Warrior and the letters "C.M.A." are British Registered Certification Trade Marks.

CABLE MAKERS ASSOCIATION, 52-54 HIGH HOLBORN, LONDON, W.C.1. Telephone: Holborn 7633

CMA/4

MODERN GAS CLEANING—I

Before you read this . . .

1. It is a means of removing solid or liquid particles from a gaseous carrying medium. It does this by charging the particles in an electric field and precipitating them onto a receiving surface.
2. It is a highly efficient means of collecting dusts, mists and fumes from most chemical and industrial processes.
3. Efficiencies of more than 99% are commonly achieved nowadays. This applies to particles of all sizes, not just those in the larger range.
4. As a rule, the material is recovered in its original state. In the cases where wet precipitators are more suitable, the material is collected as a liquid or sludge.
5. This ranges from a few hundred to several hundred thousand cubic feet per minute of gas.
6. This depends on the gas volume but an important aspect of our design is its flexibility. Simon-Carves plants can be arranged for horizontal or vertical gas flow and the proportions can be varied to suit local conditions.
7. Simon-Carves plants are robustly constructed and are designed to cope with fluctuating gas conditions with constant efficiency throughout the life of the plant. Wear and tear on the plant is very low and replacements are very infrequent.
8. Capital costs are not high considering the superior performance of electro-precipitators whilst running and maintenance costs are far less than for other types of high-efficiency collectors.

ask yourself these questions

1. WHAT IS ELECTRO-PRECIPITATION?
2. WHAT ARE ITS APPLICATIONS?
3. HOW EFFICIENT IS IT?
4. WHAT DOES IT DO TO THE MATERIAL?
5. WHAT CAPACITY CAN BE DEALT WITH?
6. HOW MUCH SPACE IS NEEDED?
7. HOW RELIABLE IS IT?
8. HOW MUCH DOES IT COST?

If you are concerned at all with problems of dust extraction for the prevention of pollution or in industrial recovery processes, you should know the answers to these key questions about the latest electro-precipitation techniques. Take time now to check on the facts you should know. The answers to the above questions are given on the left and we will be pleased to answer your further questions on electro-precipitation.

High efficiency electro-precipitation by ***Simon-Carves Ltd***

SIMON ENGINEERING GROUP

STOCKPORT, ENGLAND

OVERSEAS COMPANIES | *Simon-Carves (Africa) (Pty) Ltd: Johannesburg* *Simon-Carves (Australia) Pty Ltd: Botany, N.S.W.*

SC 156

WRITE FOR BOOKLET ON THIS SUBJECT

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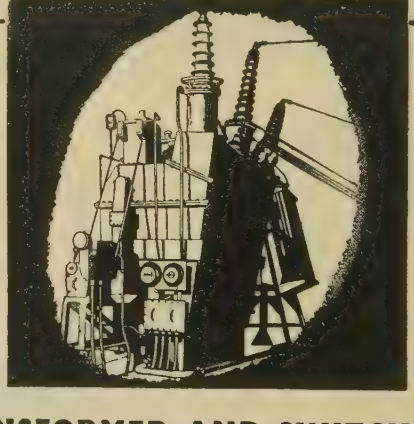
GLOVERS STANDARD CABLES "for normal distribution work can be used for vertical installation without any special precautions being necessary . . ."

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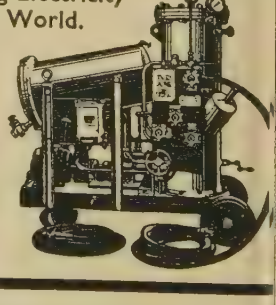
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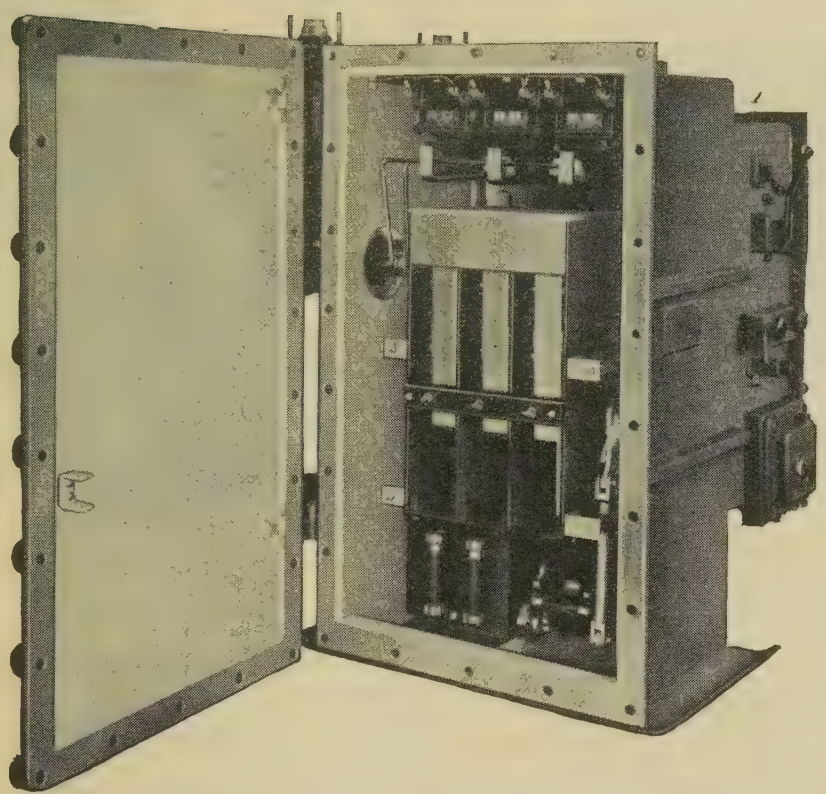


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Earth leakage protection; alternatively, *Sentryfugue* control relay for belt slip protection.

Brake Control Unit with overcurrent protection.

500 v.a. supply available for external lighting when brake control unit is not included.

Automatic sequence starting.

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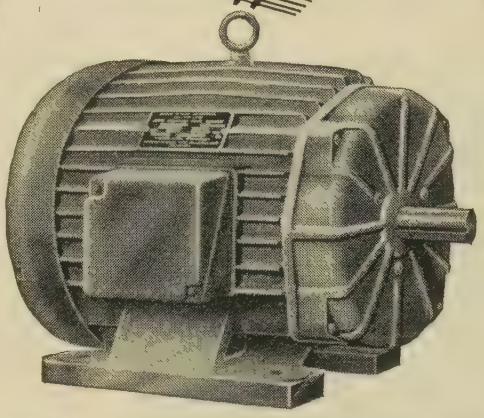
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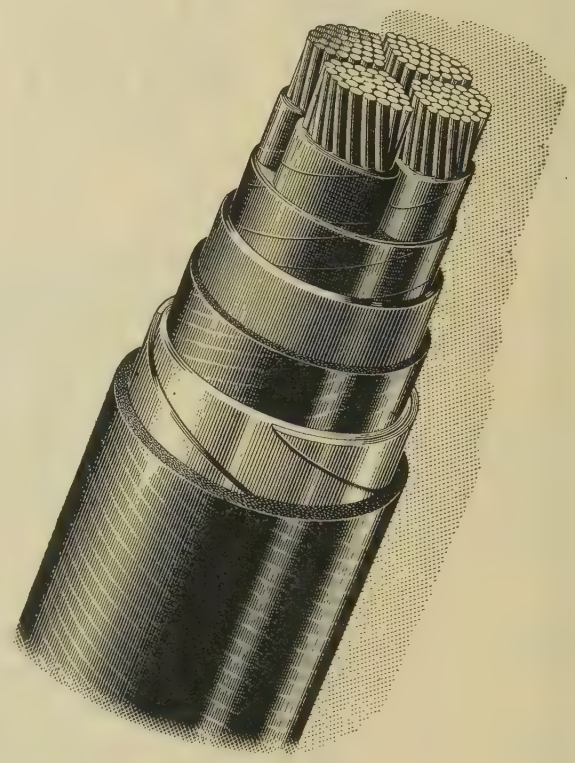
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Created for the joint design and construction of nuclear power plant in the Commonwealth and other countries, it is private industry's first international agreement in this field—and the logical outcome of Mitchell's exceptionally wide experience over the past 35 years in all branches of engineering and electrical supply.

MITCHELL COMPANIES—active in the atomic sphere since 1950—are at present engaged on three important contracts for the United Kingdom Atomic Energy Authority.

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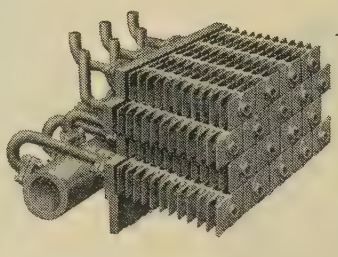
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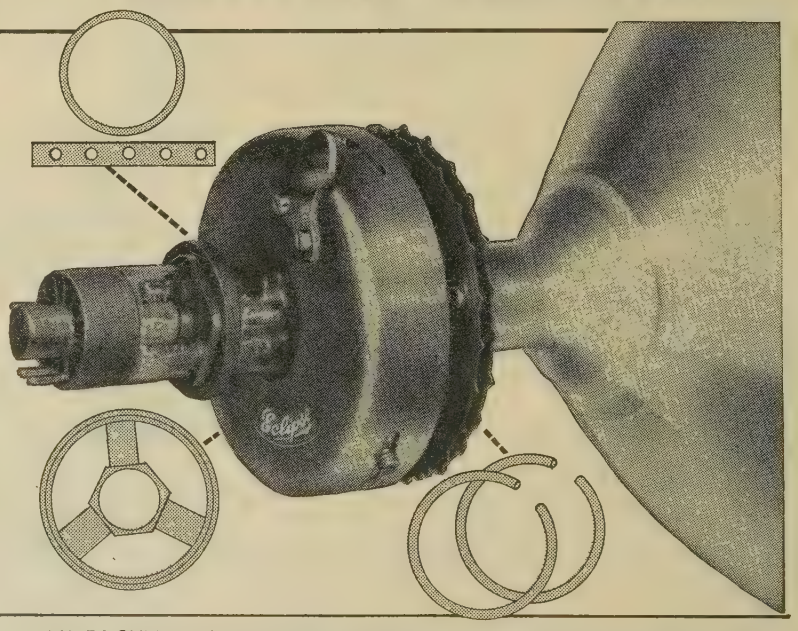
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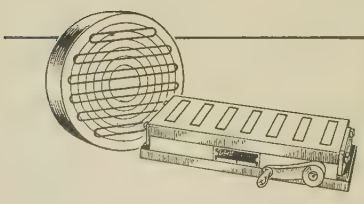
GE 166a

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PERMANENT MAGNETS *for* TELEVISION RECEIVERS

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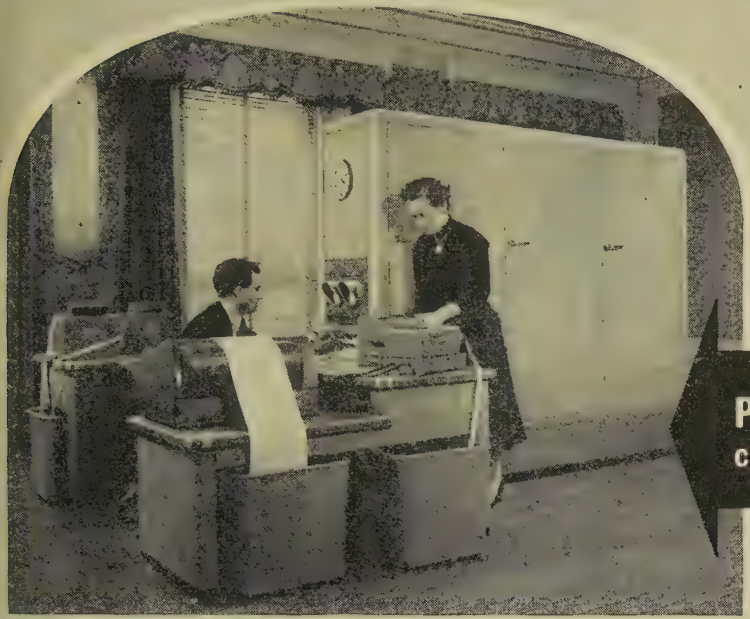
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As supplied to the Ministry of Supply for the British Army.

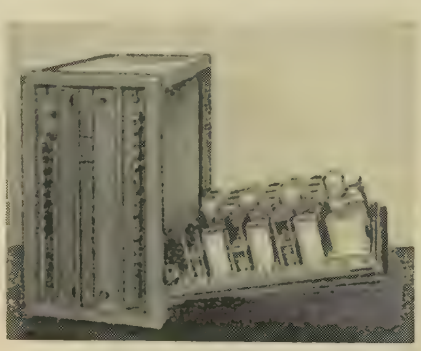
Provides 4 high quality broad band circuits 300—3,400 c/s for working over short-haul radio links transmitting a band width of 0.3—16 kc/s.
Includes 500 c/s ringers and power supplies for operation from A.C. mains or portable generators.
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For—16 dBm from the radio the output level from any channel is —4 dBm.

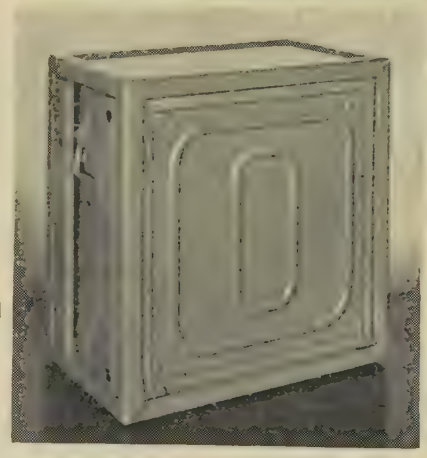
Auxiliary units are available for:—

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2 Combining 2 terminal units for 4-wire working over radio or cable circuits.

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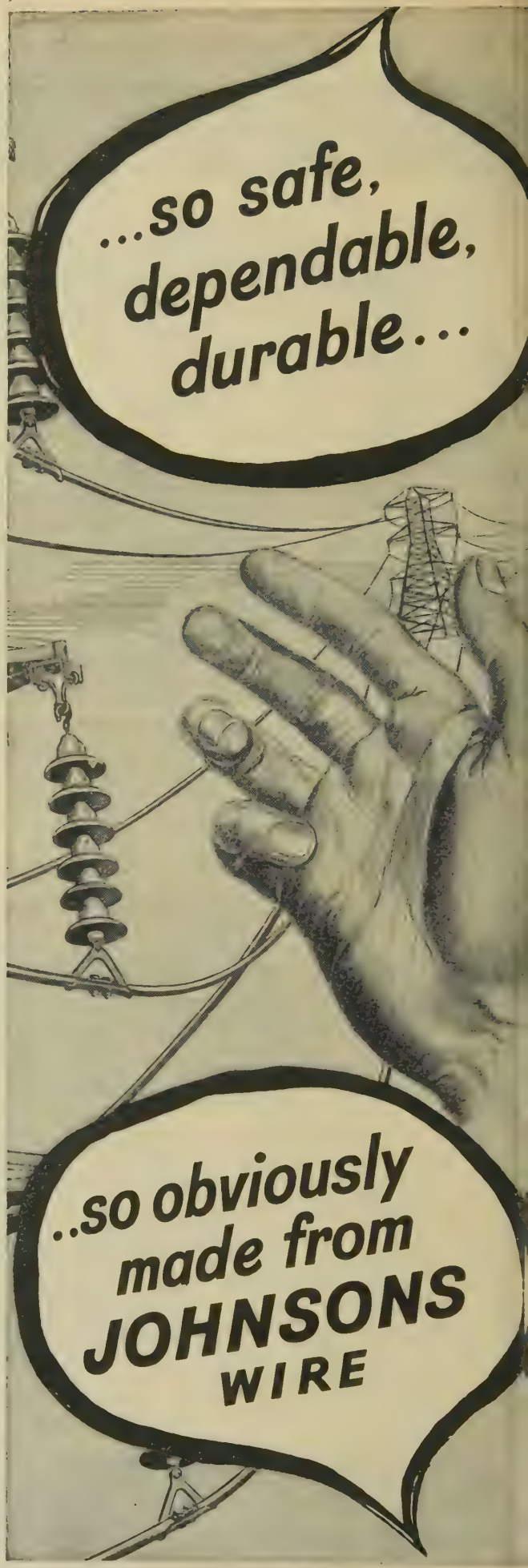
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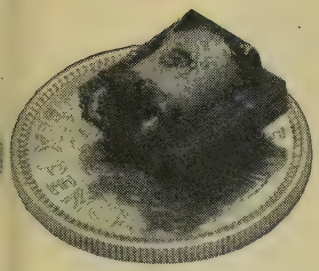
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Transformer Transformations

'Araldite' (Regd.) epoxy casting resins are used extensively by transformer manufacturers, who find that potted transformers offer many advantages.

'Araldite' casting resins provide:

- ★ **Reduced weight**
- ★ **Less bulk**
- ★ **Improved insulation**
- ★ **Excellent heat transfer**
- ★ **Reduced fire hazards**

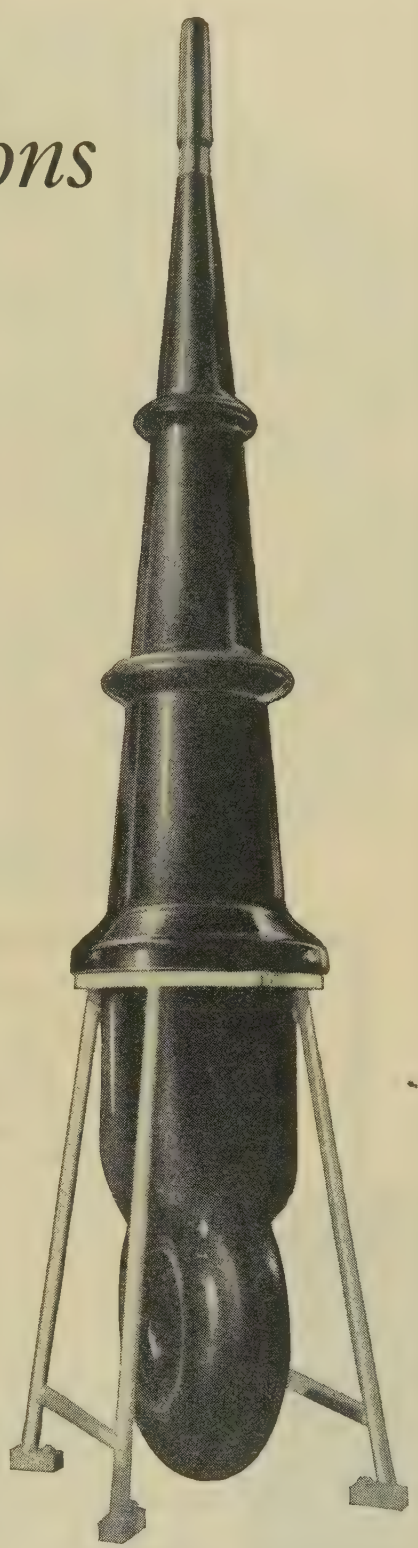
Manufacturers find that the execution of projects hitherto thought impracticable can be accomplished by the use of 'Araldite'. Outstanding adhesion to metals, ceramics, etc., combined with stability, excellent electrical properties and moisture resistance are characteristics which establish 'Araldite' as the perfect potting material for transformers and many other electrical components.

Our illustrations show a Fortiphone miniature transformer for a deaf aid (before potting) contrasted with a 400 kV. transformer incorporating 2,200 lb. of 'Araldite'.

Transformers potted with 'Araldite' comply with the tropical requirements of the Services.

'Araldite' epoxy resins have a remarkable range of characteristics and uses. *They are used*

- ★ **for bonding metals, porcelain, glass, etc.**
- ★ **for casting high grade solid insulation**
- ★ **for impregnating, potting or sealing electrical windings and components**
- ★ **for producing glass fibre laminates**
- ★ **for producing patterns, models, jigs and tools**
- ★ **as fillers for sheet metal work**
- ★ **as protective coatings for metal, wood and ceramic surfaces**



It all depends on 'ARALDITE'

'Araldite'

epoxy resins

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In the year eighteen hundred and sixty-six the ill-fated Great Eastern crossed the Atlantic to lay the first successful submarine cable linking the old world with the new by telegraph; here is one of the first spectacular achievements in guiding Electricity to the service of man.
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CHAMBERLAIN & HOOKHAM
TYPE P
PROCESS TIMERS
FOR ACCURATE AND AUTOMATIC PROCESS CONTROL



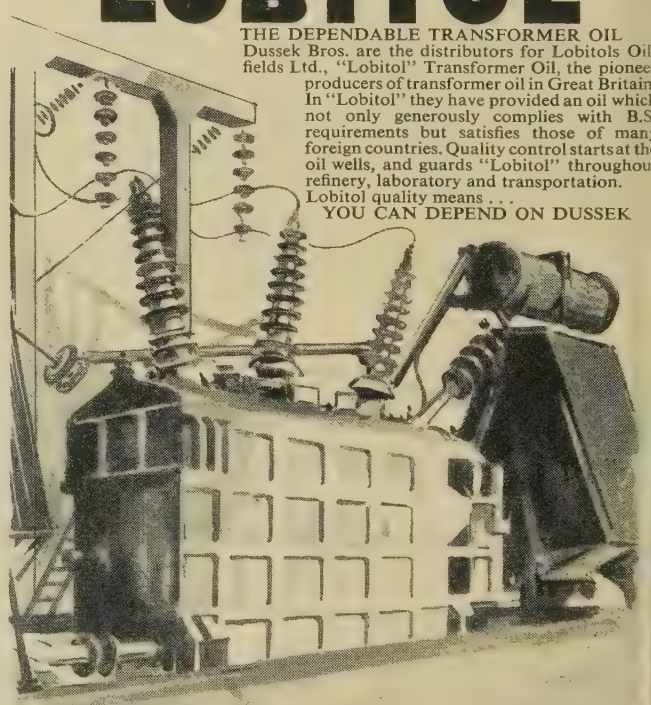
★ Scale ranges from 0-10 secs. up to 24 hours.
★ Settings down to 1/10 sec.
★ Accuracy within 0·25% of full scale range.
★ Available as single units for self-mounting or as complete control panels.
★ Any operation requiring time control by electrical means can be regulated by this instrument.

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For instance, Dewhurst & Partner are very often called upon to solve complex problems
which demand the use of Severe Duty Control equipment. Only by close co-operation
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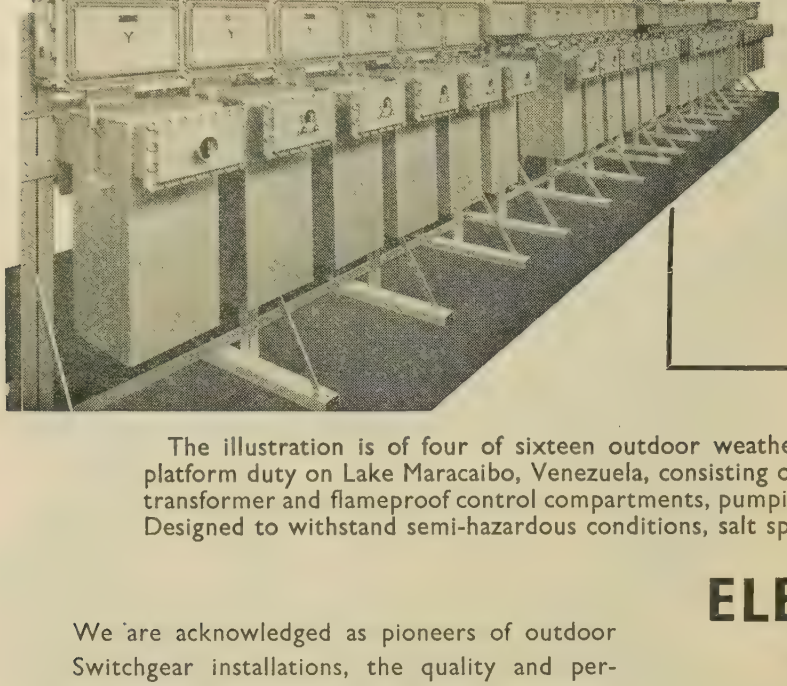
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We are acknowledged as pioneers of outdoor Switchgear installations, the quality and performance is the result of over ten years of service experience in the most severe climatic conditions at home and abroad.

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with Electronic Control

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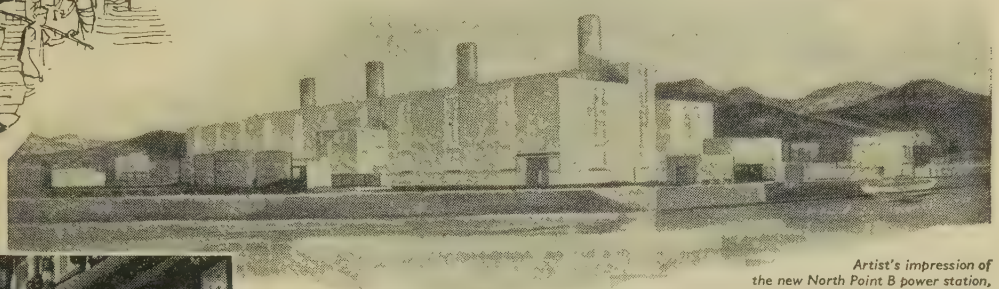
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Serving the needs of industry the world over, Davenset rectifiers and transformers are chosen for their reliability under all conditions.

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BABCOCK
Integral Furnace
BOILERS



Artist's impression of the new North Point B power station, by the courtesy of The English Electric Co. Ltd.—Engineers and directing contractors—and Messrs. Geo. Wimpey & Co. Ltd. Joint Contractors.

for the
North Point Power Stations

HONG KONG

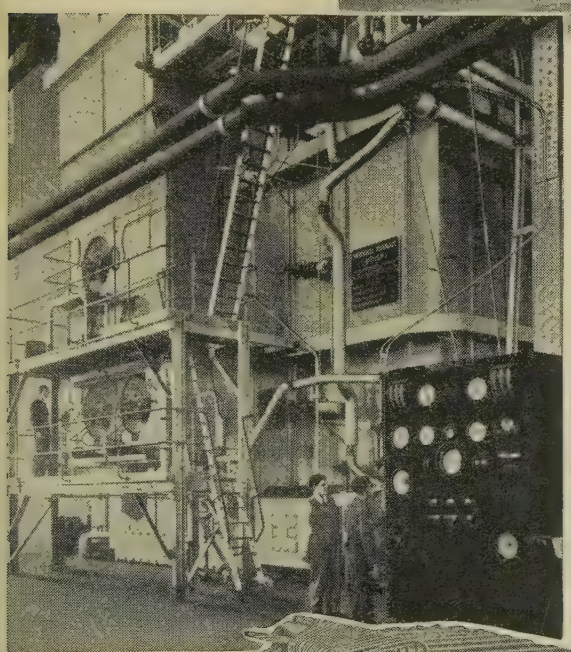
The existing North Point power station of the Hong Kong Electric Company Ltd. is equipped with 22 boilers supplied by the Babcock organization over a period of more than 40 years.

The most recent of these is the type FH oil-fired Integral Furnace boiler illustrated on the left.

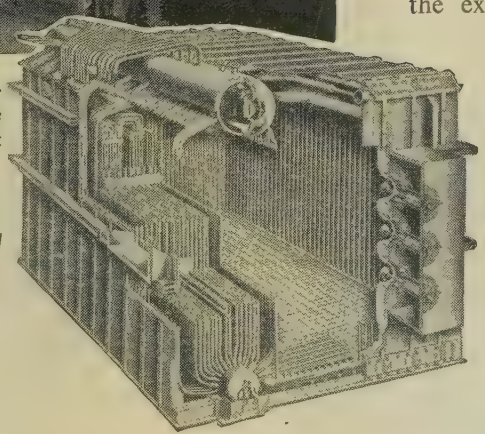
The new North Point B station, to be erected alongside the existing station, will have an ultimate capacity of 180 MW and the boiler plant already ordered by The English Electric Company Ltd., to operate the first 30 MW set, comprises a Babcock oil-fired type FH Integral Furnace unit, with a capacity of 315,000 lb./hr. MCR. at 625 lb./sq.in and 865°F, arranged for superheat control over a wide range by means of surface-type attemperators.

The Babcock Integral Furnace boiler*, with oil or pulverized-fuel firing; compact, efficient, quick steaming and flexible in operation, has been selected for many modern installations at home and overseas.

* *Ask for Publication 1525/1*



Type FH oil-fired Integral-Furnace boiler at the existing North Point power station.



Sectional view of oil-fired Integral Furnace boiler.

BABCOCK & WILCOX LTD., BABCOCK HOUSE, FARRINGDON ST., LONDON, E.C.4.



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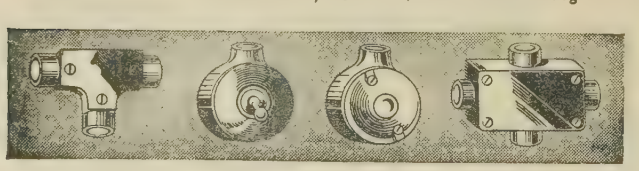
You'll seldom see it, but in many a school or factory, hospital or housing estate, METALLIC conduit and fittings plays a prominent, if under-cover, part in the electrical installation. And why is METALLIC so often specified? Because architects and contractors alike know that METALLIC is reliable, really long-lasting. Strongly made from good materials, it's specially treated to resist moisture, chemicals, etc., while consistent accuracy cuts installation time to a minimum and avoids wastage.

Wherever you go you'll find conduit and fittings by

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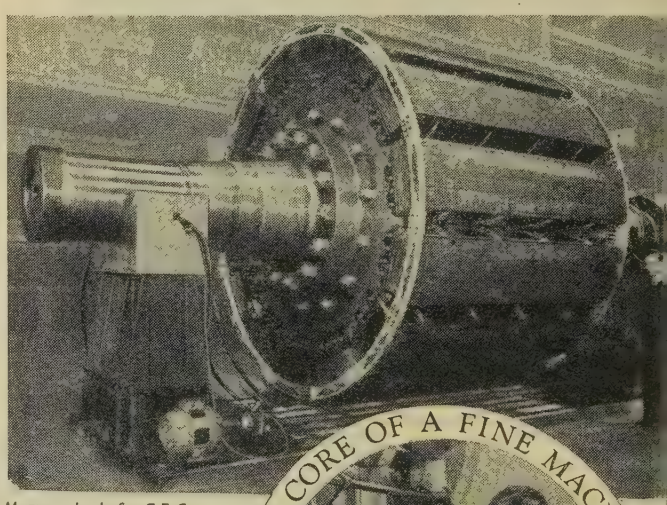
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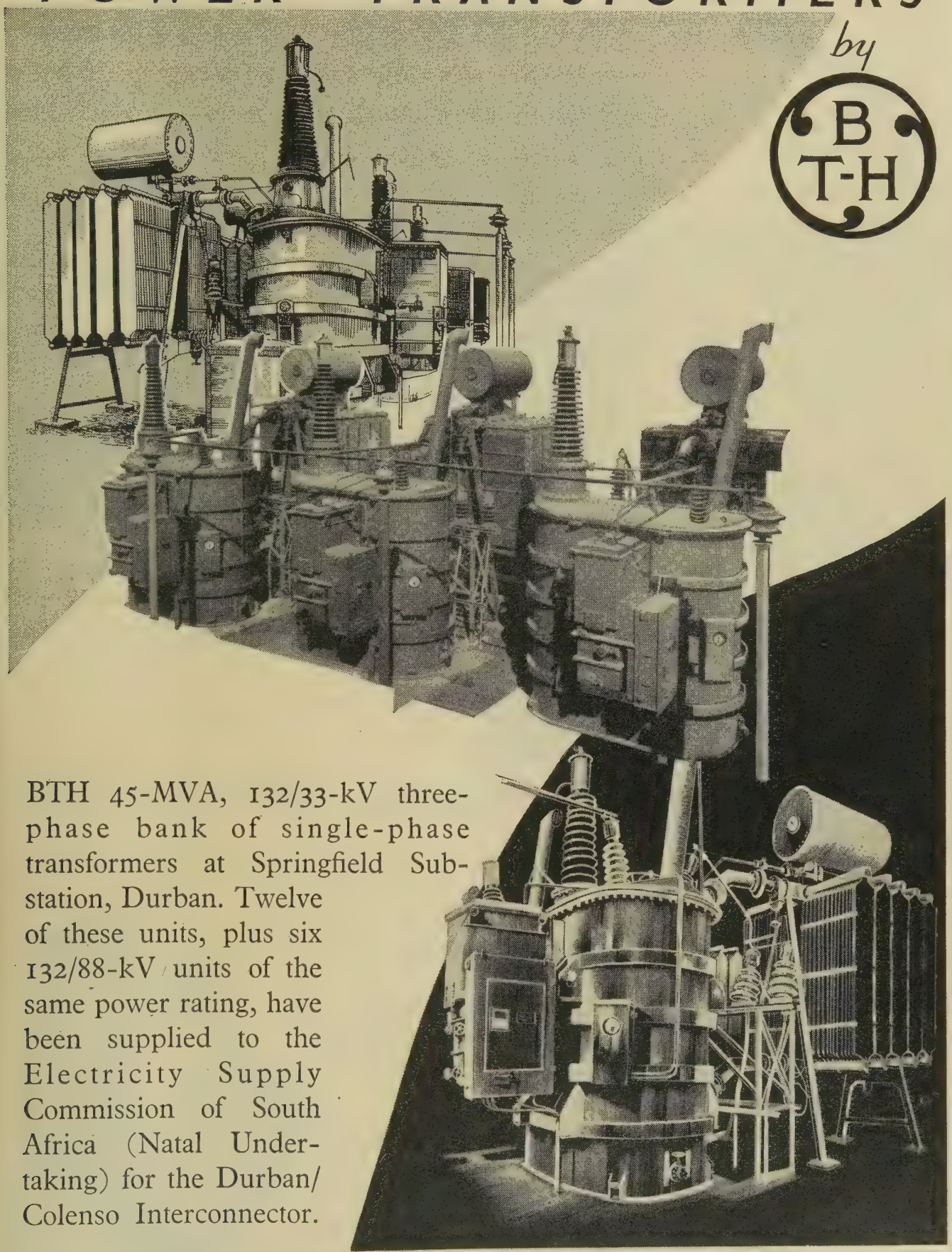
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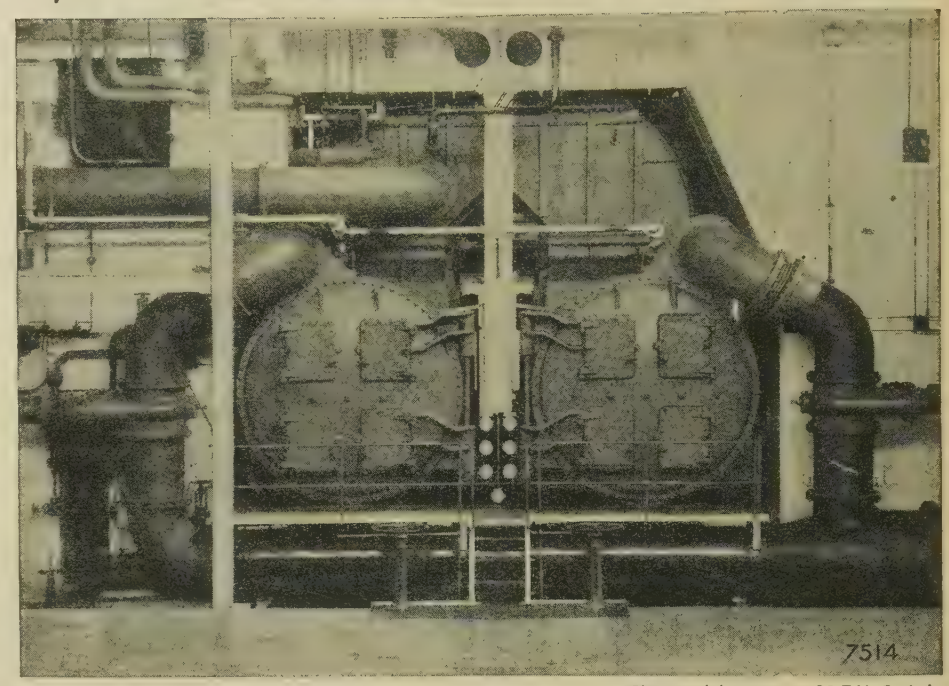
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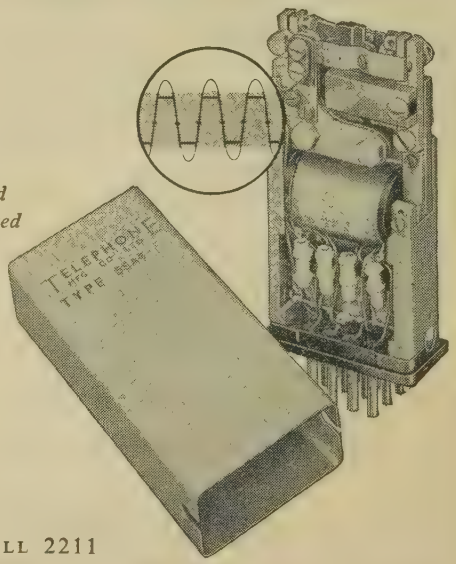
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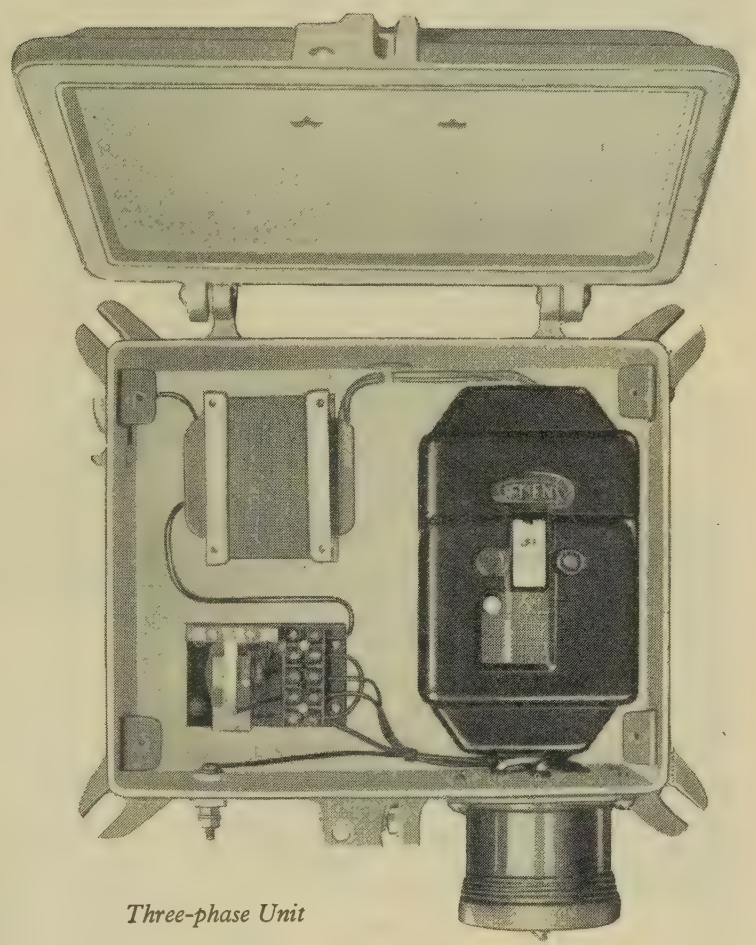
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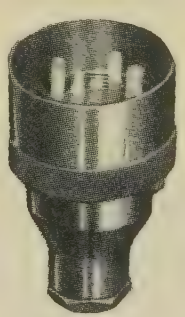
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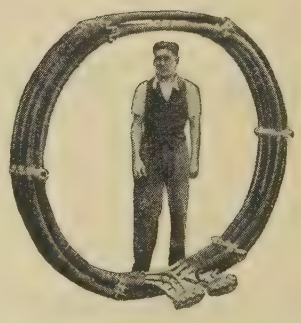
SPIRAL TUBE
Coolers

for the

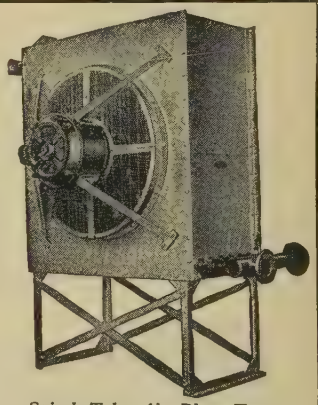
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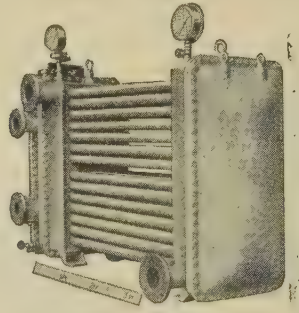
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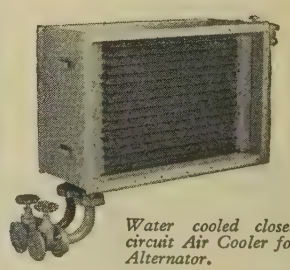
Water cooled cooling coil for Transformer.



Spiral Tube Air Blast Transformer Oil Cooler to dissipate 160 k.w.



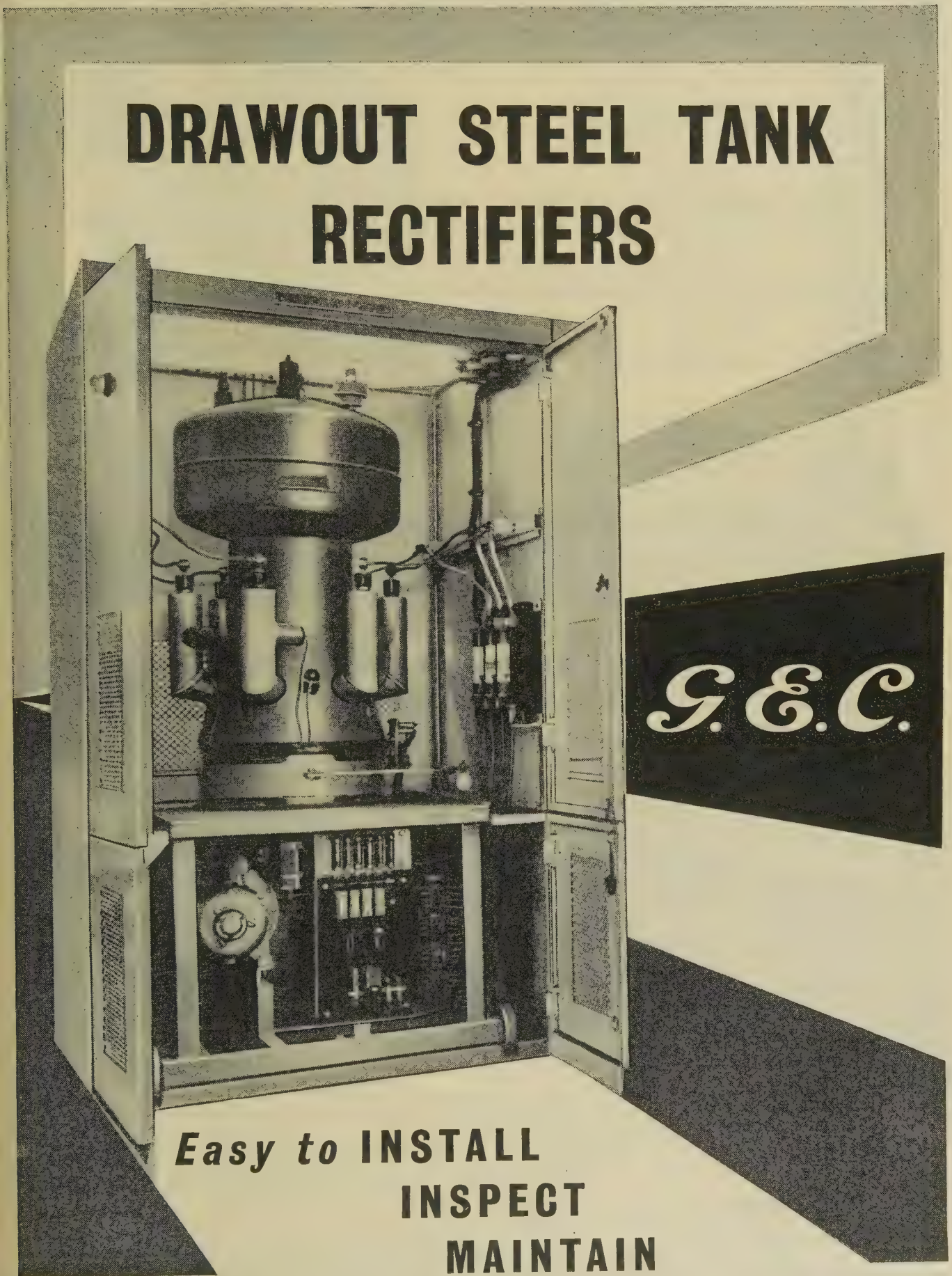
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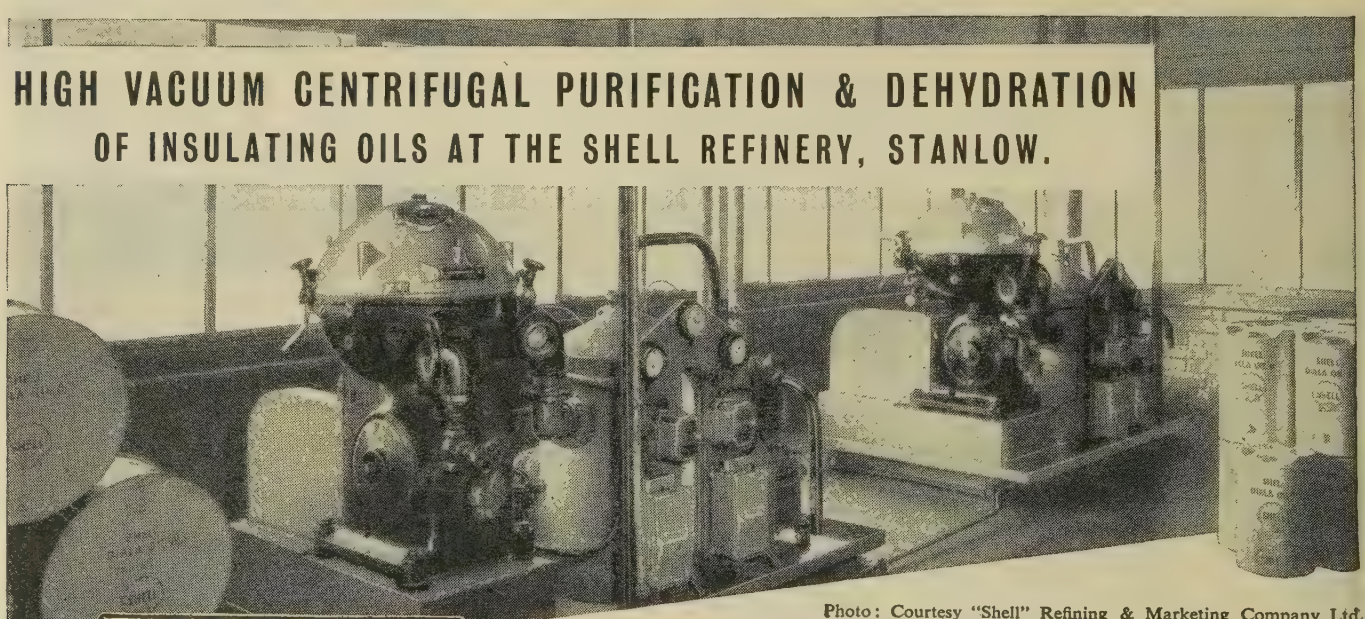


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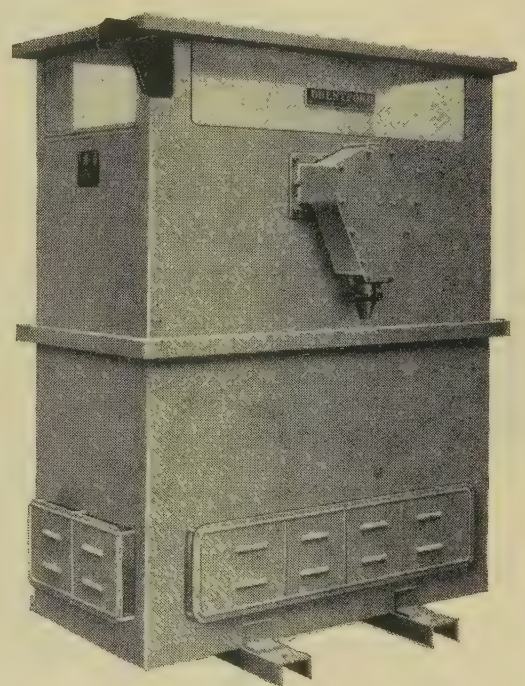
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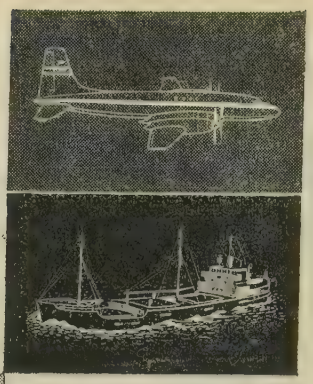
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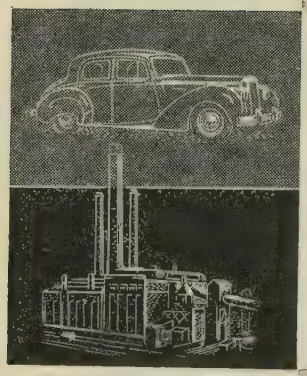
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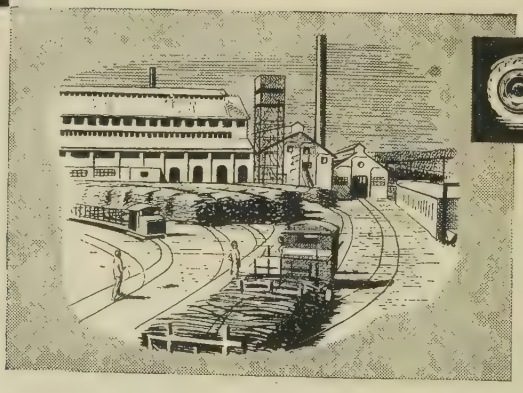
Railways throughout the world are looking to the diesel locomotive as the key to their economic recovery. British locomotives and rolling stock figure largely in re-equipment schemes, and supporting constructors of diesel locomotives the Serck organisation provide an unequalled service with comprehensive cooling systems.

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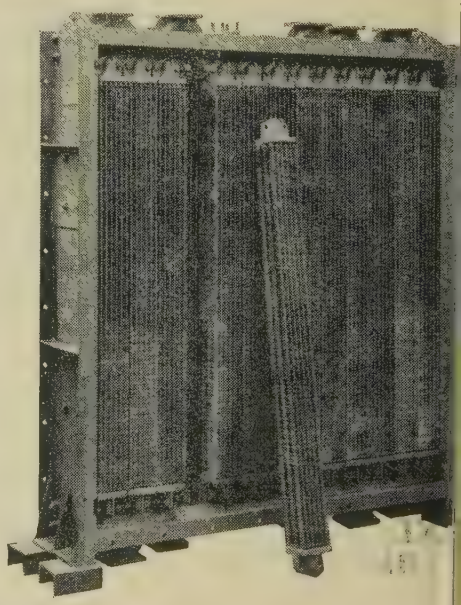


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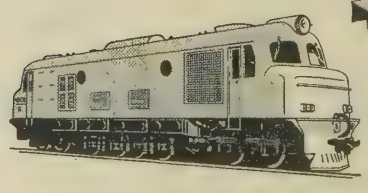


industry



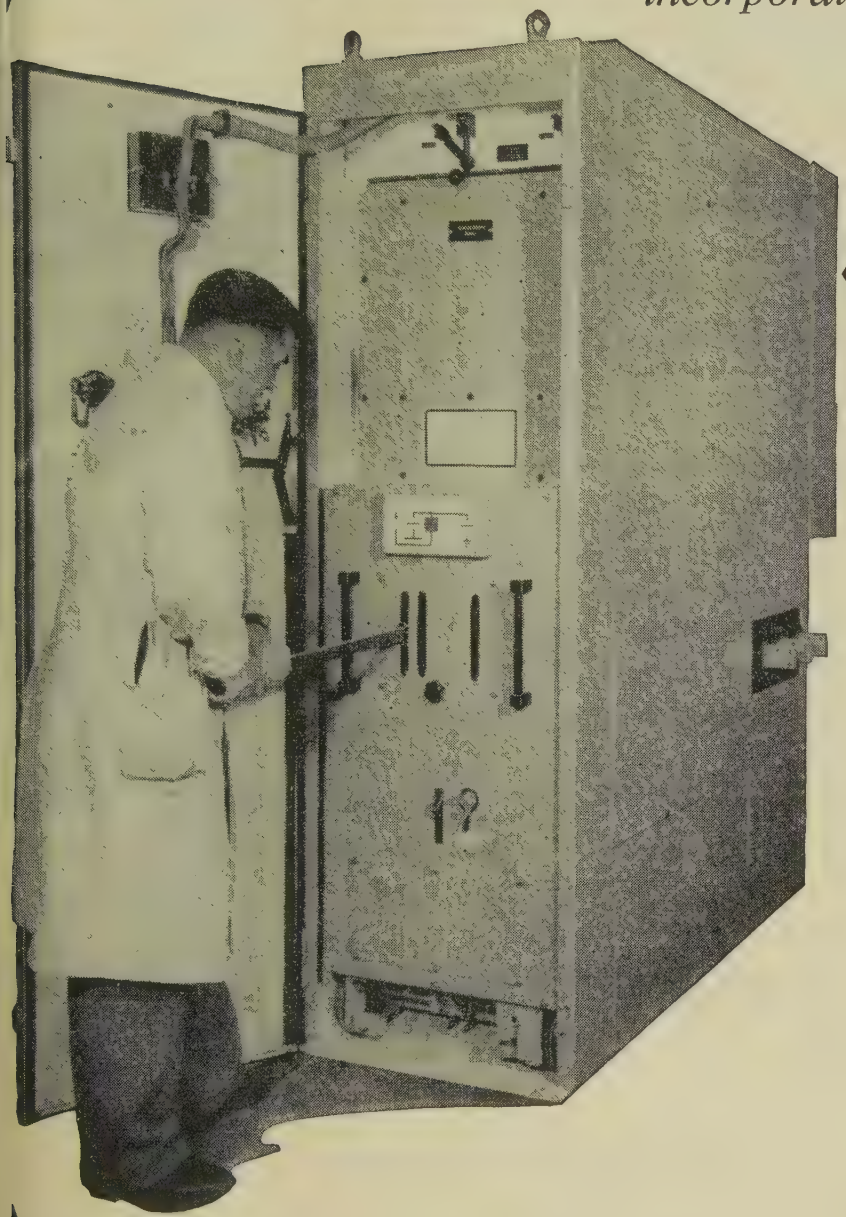
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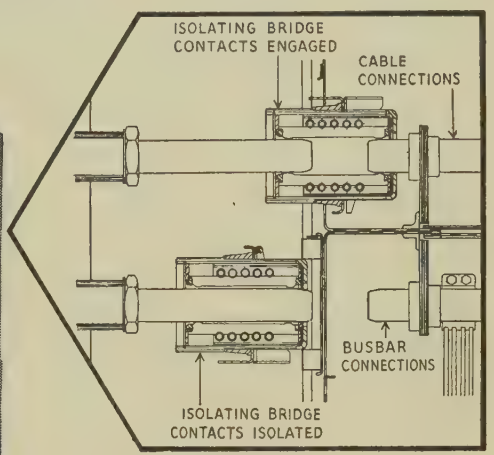
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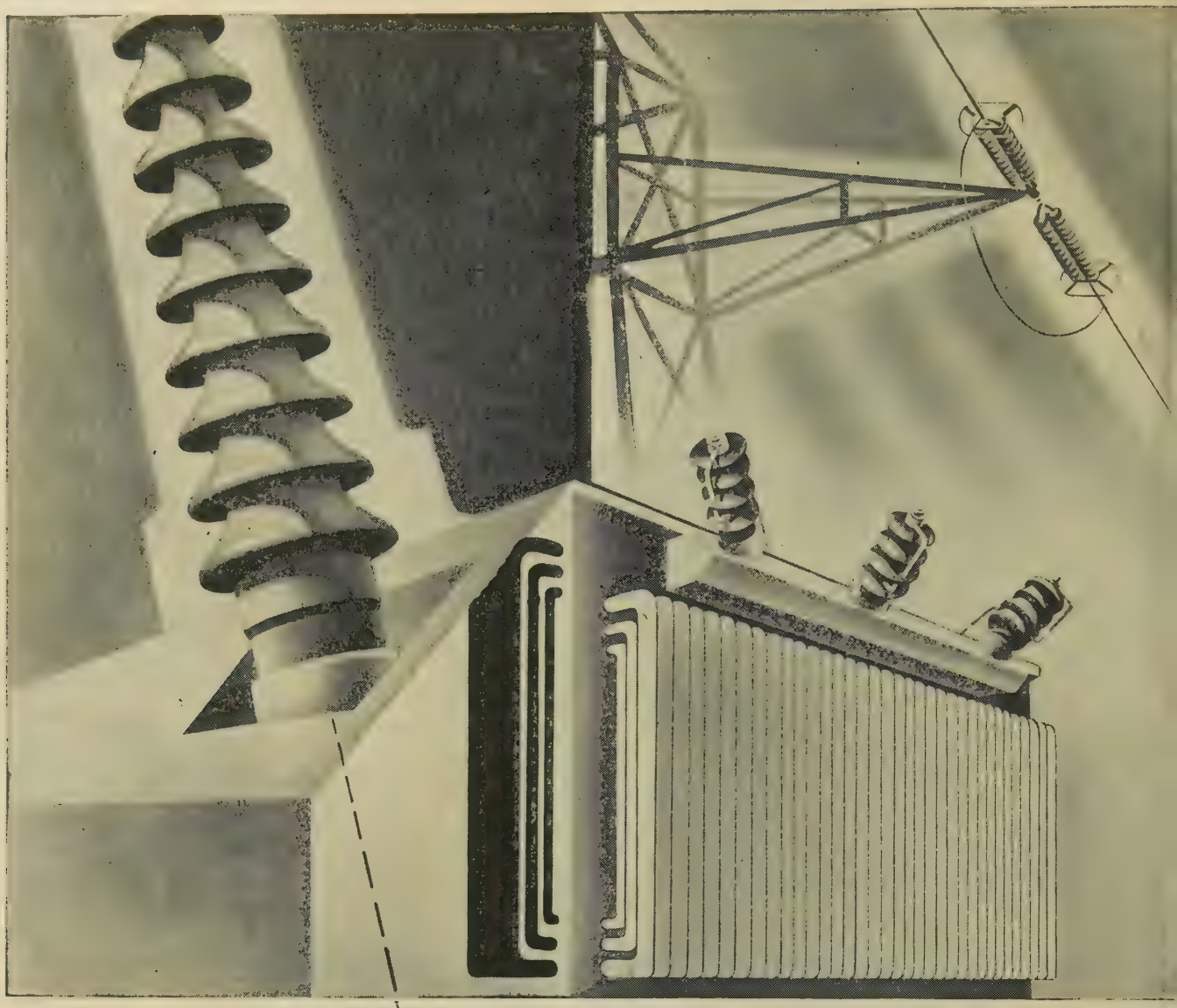
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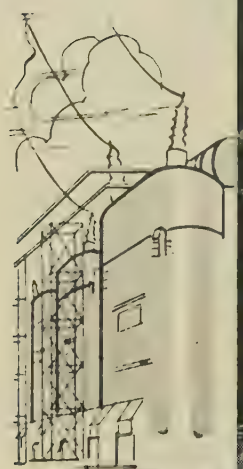
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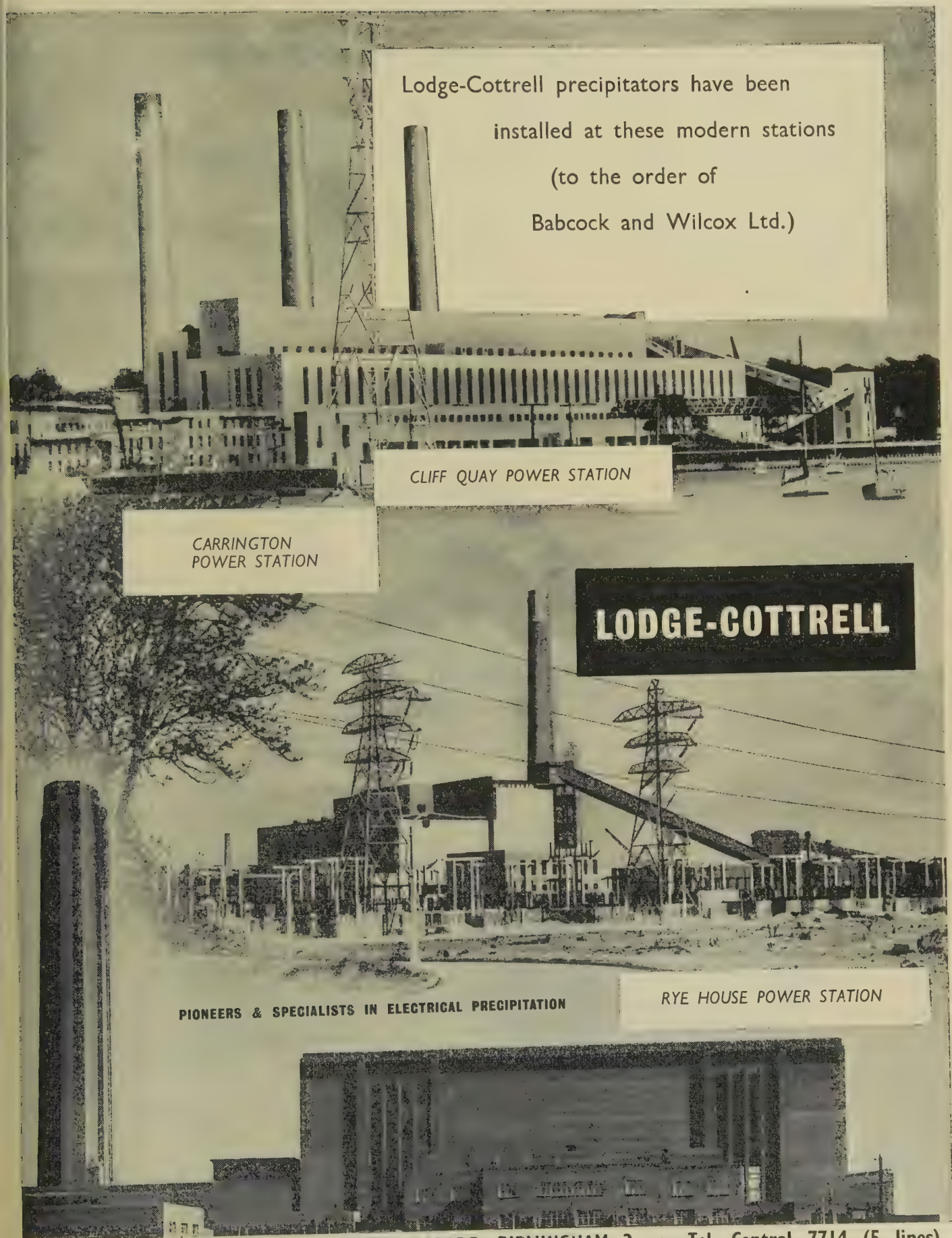


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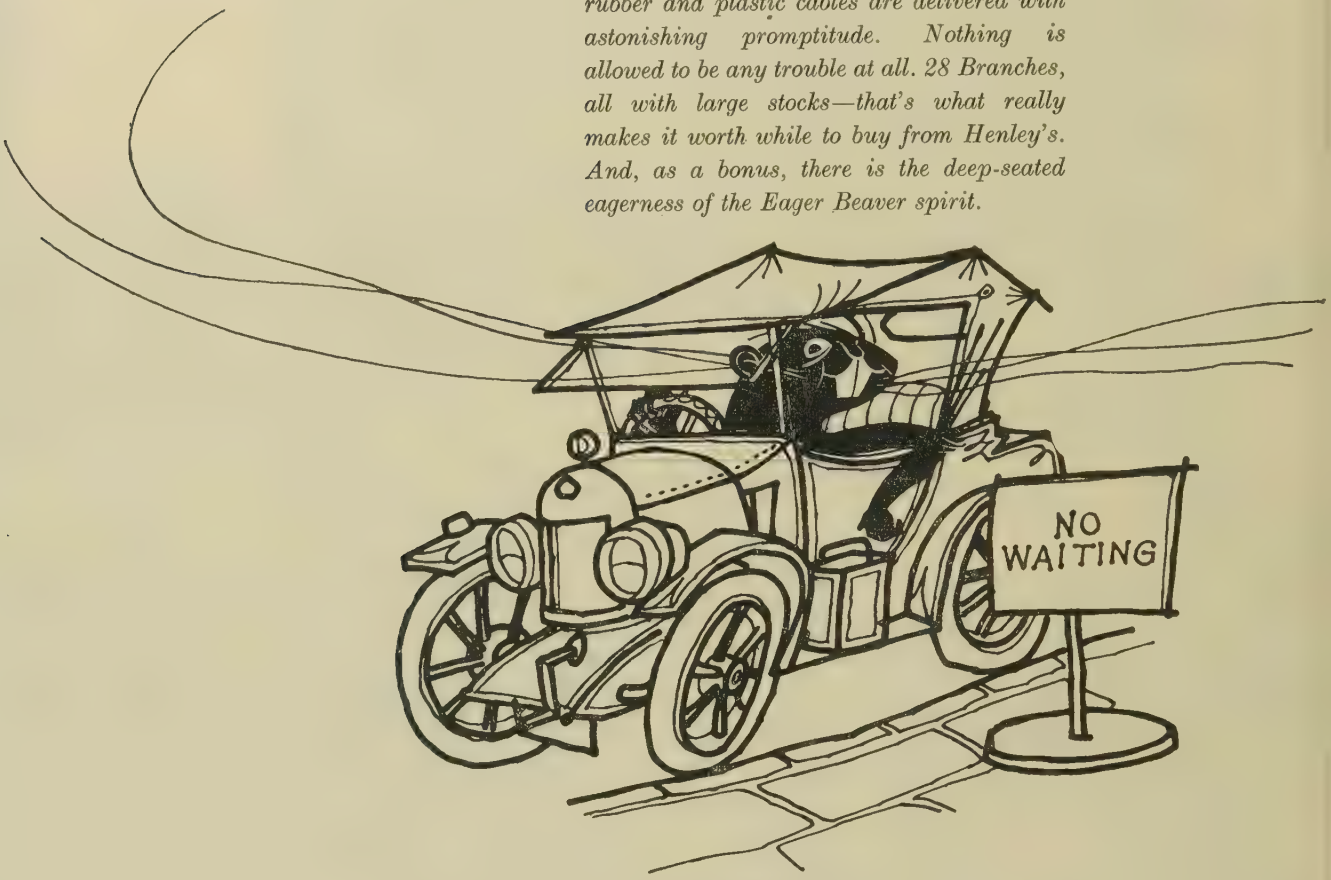
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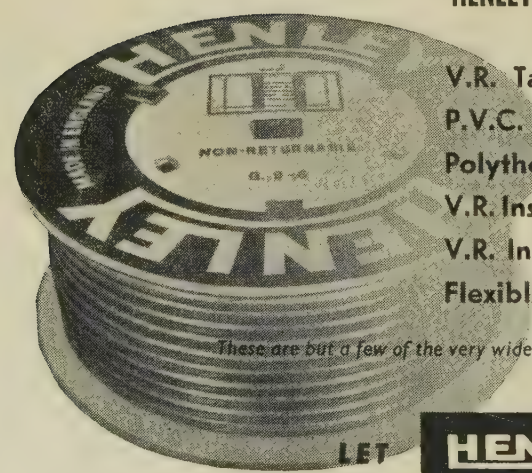
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THE INSTITUTION OF ELECTRICAL ENGINEERS

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SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By E. WILKINSON, Ph.D., B.Eng., Member.

"STRAW FOR THE BRICKS"

(ABSTRACT *of Address delivered at* ABERDEEN *7th March, and* DUNDEE *8th March*, 1956.)

It is hardly necessary to restate the need for expansion of the facilities for technical education and training, and the purpose of this address is rather to examine the means by which an adequate number of university and college entrants with suitable qualifications may be found, especially in Scotland.

Previous University Expansion

In the universities throughout the country there has already been considerable expansion since the war, and the technological student population has about doubled. Sufficient time has now elapsed, since this expansion occurred, to make an estimate of its qualitative success worth while. This may be done in various ways.

The quality of graduates may be assessed by comparing the proportion gaining honours degrees in technology to those obtaining pass degrees. In 1939 this ratio was 1·04. In 1952, in spite of larger classes, the ratio rose to 1·4 and remained at about that figure for the following years. In addition there was an appreciably higher proportion of success in post-graduate study. Taking this evidence at its face value, one can only conclude that quality has improved as well as quantity. The evidence must, however, be taken with caution because the increased numbers taking the longer honours or additional courses cannot be entirely dissociated from the more liberal financial support now available for continued study.

Some statistics of bursary awards in Scotland show that in one recent year there were 1 573 first awards to universities and that 400 were terminated because of unsatisfactory progress. The failure ratio was as high as 29·6% for boys and 16·4% for girls. Awards were also made for attendance at central institutions, where the stricter educational and marking discipline reduced the wastage by a factor of about three. Evidently there are many students who, although qualified, are either unable or unwilling to perform the work of the courses.

The Report of the Committee on Scientific Manpower, published late in 1955, put forward the views of industry on the quality of the graduate output, and many of those consulted expressed criticism of the candidates they had interviewed. The Report summed up these criticisms in rather non-committal terms without denying them.

It may reasonably be concluded from this and other evidence that further expansion cannot be achieved by an arbitrary lowering of entry standards, without endangering the quality of graduates from existing courses. This does not, however, preclude the possibility of changing the entry conditions or even of lowering them if, in suitably planned courses, the deficiencies can be made up.

The School Output in Scotland

Table 1 shows the successes gained in 1954 in the Scottish Leaving Certificate. In order to satisfy the requirements of university entrance, a candidate must have either four higher passes or three 'highers' and two 'lowers'. If the fact that entry to specific study also depends upon having passes in the right subjects be ignored then 2 836 qualify. The number of those who are deficient in only one subject amounts to 1 376, or nearly 50% as many as the qualifiers. These must be considered as potential recruits to technical or other courses.

Table 1

SCOTTISH LEAVING CERTIFICATE. PASSES IN 1954

Higher grade ↓	Lower grade → (Number of subjects) 0	1	2	3	4	5
0		224	252	169	106	25
1	87	233	361	340	135	12
2	61	239	**477**	**451**	**83**	**1**
3	**55**	**309**	655	219	5	—
4	84	499	346	27	1	—
5	296	537	148	18	1	—

Satisfactory, 2 836. Nearly satisfactory, **1 376**. Not satisfactory, 2 244

There were 2 854 entrants to Scottish universities in 1953, and the similarity of this figure to the number of qualifiers illustrates the known fact that there is not much wastage at this stage. The wastage occurs earlier, at 15 or 16 years of age.

There appear to be three ways of increasing the available entry of boys to technological courses:

(i) By ensuring that fewer able schoolboys leave school at an early age.

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(ii) By diverting talent which would otherwise pass into different educational streams, such as the arts.
(iii) By making use of candidates of slightly poorer qualifications and supplementing their preliminary education where necessary.

The first two of these may be achieved by an intensification of the information services, including personal contacts, printed pamphlets, films and television, which should not only inform the schoolboys of the careers from which they may select but also start them correctly on the right road. There is still inadequate knowledge that the engineering profession offers a life of great interest and unlimited scope. The view that reading the history of past civilizations is necessarily of more cultural significance than writing that of the present or planning that of the future needs to be dispelled.

Recruitment to Universities

During the academic year 1952–53 and the following year there were about 14 000 registered students in Scottish universities, or 0·28% of the population of the country. In England during the same two years there were about 62 400 students attending the universities, or only 0·16% of the population. Scotland may claim to be 75% ahead of England in providing places, and the ratio is even higher when the comparison is limited to technology.

It is also of interest to compare the efficiency with which the native raw material is used. Of those born in England in 1935, about 2·72% survived to enter a university about 18 years later, while in Scotland about 3·25% succeeded in doing so.

An analysis of the 1952 entry to Scottish universities demonstrates that the four chief cities sent 3·3% of their age groups to the university; the mainly industrial areas, only 1·9%; the mixed industrial and rural areas, 2·5%; and the rural areas, 4·1%. Those in outlying districts are apparently well aware of the educational facilities, though the proportion of engineering students from these areas is small. The proportion entering the faculty of arts was almost identical from all four areas, being about 43%. The 'technologies' account for the following proportions of the respective groups: 24·2%, 21·8%, 21·3% and 17·6%. The rural areas offer fewer students of technology, and, since agriculture and forestry are included in the total and may be expected to predominate, few remain for engineering. It is interesting to note that, in contrast, the rural areas provided the highest proportion of pure scientists, the figures being respectively 15·9%, 16·4%, 23·1% and 24·9%.

The small entry from the industrial areas is noteworthy. It is perhaps to be expected that, when local employers offer sufficient vacancies, a boy may be tempted to start work direct from school instead of continuing his studies.

The same symptom appears when figures relating the student population of various universities to the population of the university city are considered. The number of 'local students', i.e. those whose homes are within 30 miles of the university compared with the population of the city itself, is very low for certain industrial towns. Thus, while Edinburgh and Aberdeen provide 4·7 local students per 1 000 of the population, Cambridge 3·9 and Oxford 3·0, yet Bristol accounts for only 1·8, Nottingham 1·3 and Birmingham 1·1.

It has been suggested that perhaps 4 000 early-leavers from school would benefit by staying to take advanced courses in mathematics and science. Reviews such as these help to show where some of the talent may be found and where encouragement might usefully be given.

Women as Engineers

There is a possibility which has hardly been mentioned in this country. In the past, recruitment of women to the engineering profession has been virtually negligible, but a good case can be made out for their employment. Very few girls have studied with the object of becoming engineers, and of these many have left industry on marrying. Many engineering posts could well be filled by women, who are potentially good material to train as engineers. The statistics of bursary holders at university and college show that their performance is in one respect better than that of the men.

Their performance in the Scottish Leaving Certificate and the General Certificate of Education also compares favourably with that of the boys. It may be noted, however, that relatively few girls pursue a scientific higher school education. It is reasonable to suggest that this arises from the limited opportunities available in the past and ignorance of the possibilities which the future may hold, perhaps especially in the engineering office and the development laboratory.

If women are to be successfully employed as engineers there must be a minor social revolution to encourage many of them to continue work after marriage, since only thus is their training economically justifiable. Blocks of service flats, fully equipped with modern labour-saving devices, might offer one form of practical encouragement. The scale of financial rewards and advancement could also be designed in various ways to encourage continued working.

Early School-Leavers

Some of the early school-leavers commence an apprenticeship and enter part-time National Certificate Courses. In the past this has been a recognized and popular method of qualifying for membership of the professional institutions. The courses of study leading to membership of our own Institution have now been extended, and a purely part-time education can no longer be regarded as satisfactory, since it would take far too long. It is to be expected, therefore, that those with ability will seek transfer to alternative courses.

Universities could well consider accepting a high-level pass in the Ordinary National Certificate as a suitable entrance qualification. Entry at Higher National Certificate level hardly seems to be wise, since those who have reached this standard are already virtually a finished product and the university largely reprocesses the student to reach a similar standard. On the other hand, a bare pass at Ordinary Certificate level is not satisfactory since this appears to be the ceiling of attainment of so many. At present only about one-third of the candidates for the Ordinary Certificate successfully proceed to the Higher Certificate Course.

National Service

There is another way of increasing forthwith the usefulness of our young technologists, namely by granting complete exemption from National Service to those who have graduated from college or university courses. Neither the Services nor the engineer in training appear to benefit greatly from the present arrangement and training for industry is severely handicapped.

University or College Courses

It may fairly be assumed that, in some or all of these ways, increased numbers of trainees may be forthcoming. Not all of them will attend universities, and many will proceed to central institutions. The Higher National Diploma Courses no longer meet the new requirements of The Institution, without considerable modification. These courses were originally intended for entrants from industry, but they have largely been supported by school-leavers who have narrowly failed to qualify for a university course. There is every reason now for such schoolboys to be encouraged to remain at school until they have completed their university entrance qualification.

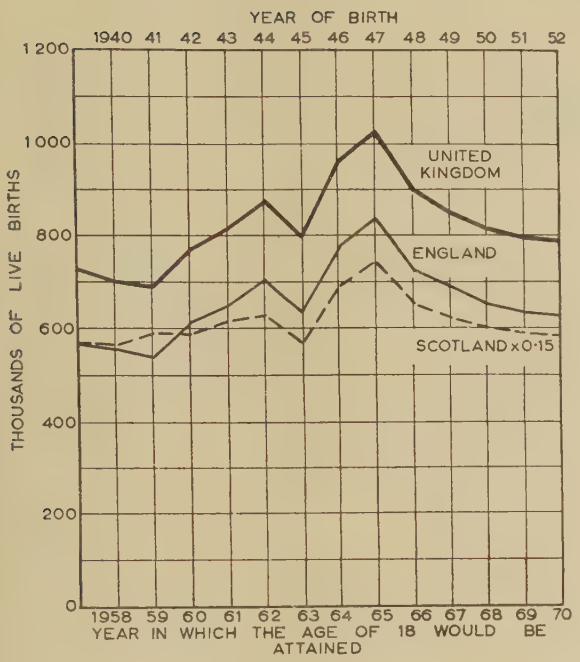


Fig. 1

In England there is now a general agreement that six-month sandwich courses lasting 4–5 years have special merit, and the system has already been widely adopted by the larger concerns. It is to be hoped that a high standard of entrance can be set, perhaps even as high as for university entrance. The prospects for sandwich courses of a similar kind are not so bright in Scotland. First, far more of the prospective students are already provided for in universities than in England. Secondly, the adolescent population is increasing at a slower rate. The 'bulge' is relatively smaller in Scotland, and the birth rate seems to have settled down at a level about 7% below that in England on a scale assuming parity eighteen years ago (see Fig. 1).

There are no electrical or mechanical industries in Scotland on the scale of those in England and covering such a wide range of manufactured products, but there are a number of first-rate firms, most of which already run apprenticeship schemes for graduates and others. Very recently these firms have formed a committee to plan a broader training course, offering widely varied experience by a pooling of their facilities. An apprentice who has had experience in a number of these establishments should be adequately trained, and a Certificate of Apprenticeship, vouched for by the Scottish Electrical Industries Training Scheme, should rank high. Indeed it may be hoped that action by this Committee may induce a few more Scots to take up engineering.

If a sandwich scheme were launched in Scotland on the English model it would provide an opportunity for National Certificate students and for some of those who, in the past, would have taken a three-year Higher National Diploma Course.

The advantages of a university course in respect of breadth of study suggest that every effort should be made to ensure that, if a student is likely to benefit by a university education, he should be admitted. At present every student who wishes to enter a Scottish University must have passed in English at the higher level, whatever he proposes to study, and this requires a knowledge of literature. It will be generally agreed that a command of English is essential for an engineering graduate, but it is surely unreasonable to require a knowledge of literature as a condition of entry to a science faculty. It would be more logical for the Scottish Universities Entrance Board and The Institution, whose demands are the same, to limit their requirements to a pass in the English Language paper alone.

This has been a critical appraisal of the material with which the industrial Britain of the future must be built, and particularly of the contribution to be made by Scotland. Britain cannot afford to lag behind its competitors in technological recruitment, and any proposals which may assist, even partly, in solving the problems of education and training merit serious consideration.

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HIGHLAND WATER POWER—THE DEVELOPMENTS OF THE NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD

By T. LAWRIE, C.B.E., F.R.S.E., M.A., M.I.Mech.E., Member

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SUMMARY

With hydro-electric schemes in the Highlands, amenity and the preservation of salmon fisheries are of great importance. Fish passes and hatcheries have been built and water falls have been opened.

There is a dam of pre-stressed concrete and the use of wet ground blast-furnace slag cement in a large gravity dam is a promising development.

Over 100 miles of tunnel have been driven and work is in hand on about a further 30 miles.

The largest individual water-turbine output is 40 MW and the highest head of water employed is 1 362 ft.

For the year 1955–56, the hydro-electric plant capacity is about 634 MW and the annual output about 1 620 million kWh; the coal equivalent of this output is about 960 000 tons, or over a fortnight's production of the Scottish coal pits. The 1955–56 output of electricity is likely to be doubled in the ensuing ten years.

In 1948, one-half of the total population of the supply area, including 93% of the farms and 99% of the crofts, were without electricity supply mains. A series of comprehensive distribution schemes are being carried out and half the farms and crofts and seven-eighths of the population are now supplied.

There is scope for developing 2 000 MW of pumped storage in the Highlands between, say, 1961 and 1975, and developments in the remoter future could be much greater.

(1) INTRODUCTION

The North of Scotland Hydro-Electric Board was set up in 1943 under the war-time Coalition Government by an Act piloted through Parliament by the then Secretary of State for Scotland, Mr. Thomas Johnston. For 14 years previously no hydro-electric scheme had been successfully promoted in Scotland although a half-dozen different promotions had failed and, as the late Lord Cooper—recently Lord Justice General and President of the Court of Session—pointed out in his famous Report in 1942, the whole subject had become involved in an atmosphere of grievance, suspicion, prejudice and embittered controversy. With the object of making a fresh start, the Cooper Report recommended that a public Board be set up to carry out future water-power development and that safeguards be provided both for public and private interests. Provision was accordingly made in the Act that hydro-electric schemes should be published, and there should be an Amenity Committee and a Fisheries Committee to advise the Board and the Secretary of State, that, if necessary, a public inquiry should be held, and that each scheme should be laid before both Houses of Parliament for 40 days, during which time a motion could be made for its annulment.

The development of water power in the Highlands of Scotland is the principal duty of the Board, but it was also made responsible for the distribution of electricity in the West Highlands and the Islands, where no supply authority was operating, and in 1948 it became responsible for distribution in that part of Scotland which lies north and west of the Firth of Tay and the Firth of Clyde—part mountainous, part crofting, part agricultural—about three-quarters of the land area of Scotland, and containing one-quarter of the population of the country (see Fig. 1). The Board also operates steam stations at Dundee and Aberdeen, and Diesel stations in some of the Islands where water power is not available, and it is experimenting with an oil-fired gas turbine, the development of peat as a gas-turbine fuel and with wind power, so that the variety of prime movers is considerable.

The Board is unique in one respect, which is of particular importance to a sparsely populated area like the Highlands: it is required to collaborate as far as its duties and powers permit in measures for the economic development and social improvement of its supply area; so it is not solely an electrical Board; it is also a social and economic reconstruction and welfare Board whose operations must be of a thoroughly practical nature, for it has to make ends meet.

(2) WATER POWER—OLD AND NEW

It is interesting to glance back at the water-power developments of the past. Modern water turbines are a product of the last 60 years or so, but the old mill wheels were the foundation of many a country industry. There were, for example, 43 mills along the course of the River Leven in Fife, which flows out of Loch Leven, famous for its trout fishing, and the many industries served by that power included spinning-mills, bleachfields, corn-mills (several in each class), two sawmills, a wool-mill, a flour-mill, a lint-mill, a snuff-mill, a distillery, a flint-mill, and a foundry. Probably the most famous of the old wheels were at the Mills of Catrine in Ayrshire and Deanston on the River Teith in Perthshire. The former was built in 1827 and contained two large wheels operating on a fall of 48 ft (originally divided into two stages of 24 ft each) and producing 250 h.p. at a speed of 2 r.p.m.; in 1863 the speed was increased to 3 r.p.m. and the power to 500 h.p. They were replaced in 1947 by an electric drive. At Deanston, four large wheels, 36 ft in diameter, were installed shortly after 1807. They produced 400 h.p. and continued to run until 1951.

Before the Hydro-Electric Board came into existence the principal water-power developments in Scotland were the industrial developments of the British Aluminium Company at Foyers, Kinlochleven and Fort William, producing an aggregate of 111 000 kW of d.c. energy with an annual output of about 600 million kWh and three public supply schemes, namely the Grampian Scheme, promoted in 1922, the Lanarkshire Hydro-Electric Scheme, promoted in 1924, and the Galloway Scheme, promoted in 1929. Their aggregate capacity amounts to 188 000 kW producing a.c. energy amounting to about 593 million kWh per annum.

Most modern hydro-electric schemes consist of a dam to impound and store water, a tunnel to convey the water through the mountains and a power station where water turbines and electric generators turn the water power into electricity. Occasionally, however, the dam and power station may be combined

Mr. Lawrie, who died on the 13th August, 1955, was with the North of Scotland Hydro-Electric Board.

The paper was read at the meetings by Mr. A. A. Fulton and Mr. C. L. Allan.

Fig. 1.—North of Scotland Hydro-Electric Board.
Map of power stations and transmission lines.

KEY

- Hydro-electric stations.
- Diesel-electric stations.
- Steam stations.
- 132 kV transmission lines.
- C.C. Control centre.



in one structure which extends across the river valley, and no tunnel may be needed. Often there are subsidiary works for diverting additional water into the catchment area; sometimes, although more often in the past than nowadays, pipelines are to be seen running down the hillside to feed power stations, and sometimes the power station is built deep in the bowels of the earth, vertically below the dam, and the function of the tunnel is simply to carry away the tail water. However, there is much to be done before a hydro-electric scheme reaches the constructional stage. First comes the preliminary surveying, then the various works have to be considered. The line for a dam is governed by the narrowest or most economical site which can be secured with good rock foundations. Similarly, the line for a tunnel must traverse good rock, if possible, and if the tunnel is a long one there are advantages in being able to get in at intermediate points so as to drive it from several faces at once. Where a power station is concerned, good foundations are again of great importance and questions of access and transport of heavy machinery must be considered.

The preparation of a scheme, however, involves more than surveying and deciding upon sites for the works. In the first place, amenity is of great importance. Concrete power stations may be ugly and there are questions of design and of material—stone or brick and roughcast with a whitewash finish, for example. Surface pipelines must be avoided, if practicable, and in all these matters the Board are helped by the Amenity Committee. Secondly, there are salmon; these are of great importance and are discussed in Section 2.1.

(2.1) Salmon and Hydro-Electric Schemes

One of the most interesting aspects of water-power development is its interrelation with salmon fishing and the stock of fish. Salmon are migratory. They spawn in the gravel of rivers and streams in November, and the young alevins hatch out in the spring, and after spending the first two years of their lives in fresh water, they migrate downstream to the sea. At that stage they are called "smolts" and are between five and six inches long. The next 1–4 years are spent in the sea, and not much is known about that period of their lives. Then, with the urge to return to breed, the salmon approach land again and swim along the coast seeking the river in which they were born. At that time, they are of importance to the commercial net fishings along the coast and in the estuaries, and most of the market supplies are caught there. The salmon which escape the nets are said to detect by some mysterious means the taste or chemical composition of the water they once knew, and swim up the rivers, giving good sport as they go; they travel with immense determination for many difficult miles upstream, past rapids and even waterfalls of considerable height, to the remote gravel patches where, in November, they spawn and start the life cycle over again.

Hydro-electric schemes may affect the salmon in at least four important ways. If a dam is thrown across a salmon river, a fish pass must be provided. If a reservoir floods out the gravels which have been used by spawning fish, care must be taken either to see that sufficient alternative natural spawning is available or that a hatchery is provided. If water is taken away from its natural course through a tunnel to a power station, compensation water must be let down so that fish life can be maintained, and, finally, the smolts must be able to migrate downstream to the sea past those hydro-electric works which interfere with the normal flow of water.

The fish passes which enable salmon to surmount dams have gradually been developed from the simple "slap" in a mill dam through various types of what may be described as a staircase or ladder of pools to the modern pass, invented by Mr. Borland of Kilmarnock, in which fish are first attracted into the bottom end of a large pipe on the downstream face of a dam; the outlet of the pipe is then closed and as water continues to pour in, the level rises and the fish rise effortlessly with it until they have reached the upstream end and can swim on into the reservoir.

At Pitlochry, on the River Tummel in Central Perthshire, there is one of the best-known fish passes of the pool type. The water level rises 18 in from each pool to the next, and each pool is connected to the next by a submerged pipe. Glass windows have been let into the sides of two pools so that the fish can be seen as they swim up (Fig. 2); at times when there is a big run of fish, over 200 have been seen to come up in a single day, and during each of the seasons 1951–1954 the total number which went up was in the neighbourhood of 5 500. They were counted by watchers but, in addition, an electric counter has been devised which, after two years of experiment, gives very accurate results, and can even discriminate between salmon of over 6 lb and grilse of under 6 lb, and between ascending and descending fish. The counter works on the Wheatstone bridge principle, the slight difference in resistance between plain water and water with a fish swimming past being multiplied by electronic means to provide enough power to operate a cyclometer counter. The discrimination between fish of over and under 6 lb depends on the difference in resistance with the smaller fish being less than with the larger ones. Two counters a few feet apart are used and ascending fish naturally cause an impulse in the lower one first and descending fish in the upper one first.

In two cases already, hatcheries have been built, one for the River Garry in Inverness-shire, and one for the tributaries of the River Conon in Ross and Cromarty. The fry, when they hatch out, are distributed widely in the neighbouring rivers and lochs, so that they will have the best chance of finding food and of avoiding predatory birds and fish. In two other cases—on the River Conon in Ross and Cromarty and the River Lochay near Killin in Perthshire—waterfalls at present impassable to salmon are being opened up so as to provide access to new stretches of river for spawning and thus make up for stretches elsewhere which are to be submerged by new reservoirs.

Although falls on the Conon are now opened up and fry are also being planted out to establish a new run of fish, the young smolts will still face the hazard of predatory fish in Loch Luichart and other smaller lochs which they have to pass through on their way to the sea. Heavy attacks have therefore been made on predatory fish in these lochs and in three years, 5 656 pike, 33 495 perch and many eels have been destroyed.

While some waterfalls are impassable to salmon, it may be of interest to say what height of fall they can ascend. They succeed in large numbers in getting up the Falls of Shin in Sutherlandshire when the water has lost its spring chill and the volume coming over the Falls is not too great. The height of the jump there, depending on water conditions, is probably about 7 ft. A still higher jump is at the Falls of Orrin in Ross and Cromarty where, when conditions are right, the fish actually get up about 10 ft.

When salmon have surmounted the hydro-electric dams and have spawned, the young smolts have to migrate downstream to the sea, and if the pressure in the turbines of a hydro-electric station is not too high, the smolts pass through without damage; the flow of water through the machinery is smooth, but the spaces between the turbine blades and between the vanes of the guide apparatus must obviously be wide enough for safety. Smolts for some 16 years now have been going through turbines with a pressure of 120 ft head of water in Galloway in South West Scotland. They have also successfully withstood laboratory tests at about 100 lb/in^2, roughly equivalent to a 200 ft head of water. The Hydro-Electric Board has three power stations through which salmon are allowed to pass. These are at Moran

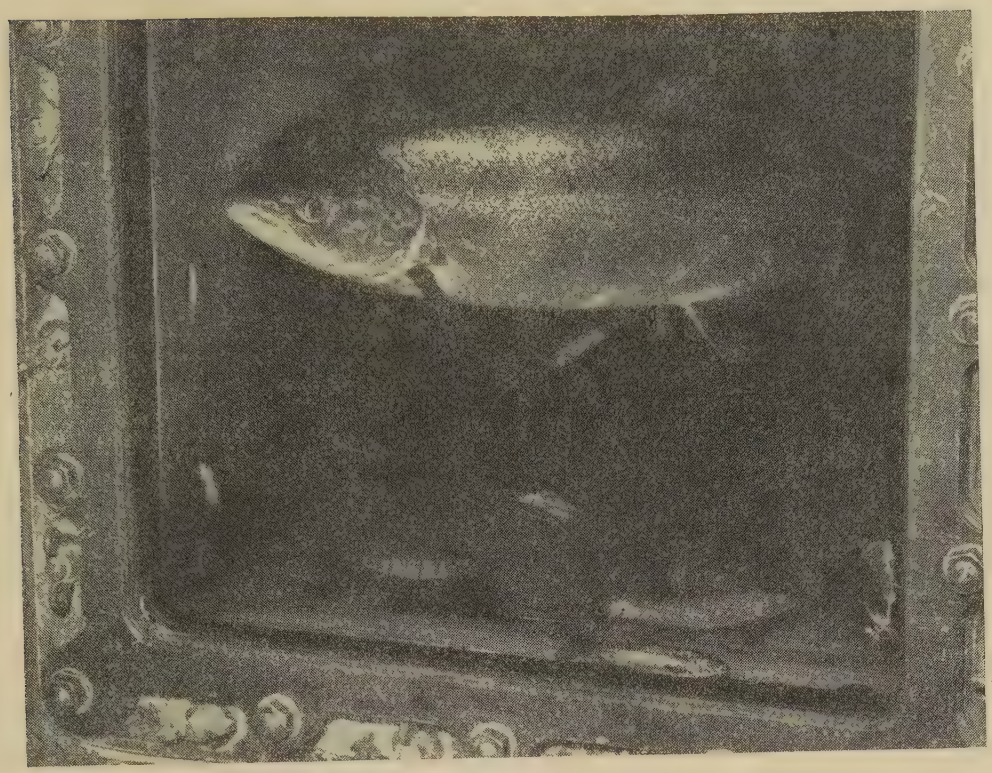


Fig. 2.—A salmon and some smolts in the fish pass at Pitlochry.
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where the head is 17 ft, at Pitlochry where it is 55 ft, and at Torr Achilty where it is 45ft, so the margin of safety is substantial.

Where, however, the pressure in the turbines is high, the smolts would probably not survive the passage and screens are required at the intakes of tunnels to keep them out and to guide them towards the fish-pass entrance where they can safely descend. These screens have to be of large area so that the speed of the current of water through them does not exceed about 1 ft/sec; that is slow enough to avoid much risk of the smolts being pinned to the screens by the speed of the water and killed.

(2.2) Dams

Usually in these hydro-electric schemes, the spectacular works are also those of greatest technical interest. The highest dam in Scotland, for instance, is the Sloy dam, 168 ft from base to spillway, and the first of the buttress type to be built in this country. The Mullardoch dam—part of the Affric Scheme—is the most massive, being of the solid gravity type 2 385 ft long and 116 ft high and built so that its centre is over what was once a rocky island at the outlet of the loch.

That particular rocky island had an interesting link with the past, because on it were discovered some old foundations. The young engineer who found them thought they were the foundations of an anti-aircraft gun and he wondered why they should be placed in that remote and mountainous spot. An older man, a native more versed in local lore, however, was able to tell him that they were all that was left of the last illicit still in the neighbourhood.

There are three more dams of the buttress type, one at Glen Shira in Argyllshire near Inveraray, one in Glen Errochty in Central Perthshire and one at Lawers near Killin, Perthshire. This buttress type of dam not only has a fine and strong appearance, but is of particular advantage in these times because the design enables a substantial tonnage of cement to be saved.

There is still more novel and economical development in dam construction in Glen Moriston in Inverness-shire, where blast-furnace slag is ground wet and mixed with cement by the Trief process, as has been recently done at the Bort Dam in France. This process has the double advantage of effecting about a 60% economy in cement and making use of the slag which was hitherto of little commercial value.

In addition, however, with the object of saving still more cement, the Board build rockfill and earthfill dams. The largest rockfill dam is at the outlet of Loch Quoich in Glen Garry, Inverness-shire. Its maximum height is 122 ft and its length 1 100 ft.

The latest type of dam which the Board are constructing is the prestressed concrete dam at Allt na Lairige in Glen Fyne, Argyllshire (Fig. 3). It is the first time that a new dam has been built on this principle, although it has already been adopted abroad for heightening existing dams. The dam will have a maximum height of 73 ft and a length of 1 375 ft, and the "prestressing" is provided by groups of steel rods which hold the dam down to the rock with less expense than mass concrete.

(2.3) Tunnelling

When tunnelling began on the Hydro-Electric Board's works, immediately after the war, a start had to be made from scratch since very little tunnelling had been done in the country for many years and there were very few trained tunnellers left. As the various contracts have proceeded, however, a steadily increasing number of men have gained experience. The length of tunnels driven by 1955 totals over 100 miles, and work is in hand on a further 30 miles. They vary in size from the Clunie tunnel at Pitlochry, which is 23ft in diameter and 2 miles long—the largest water-conveying tunnel in the country—to 6 ft 7 in tunnels on the Striven Scheme near Dunoon, which are about the smallest size suitable for the working convenience of men and machinery.

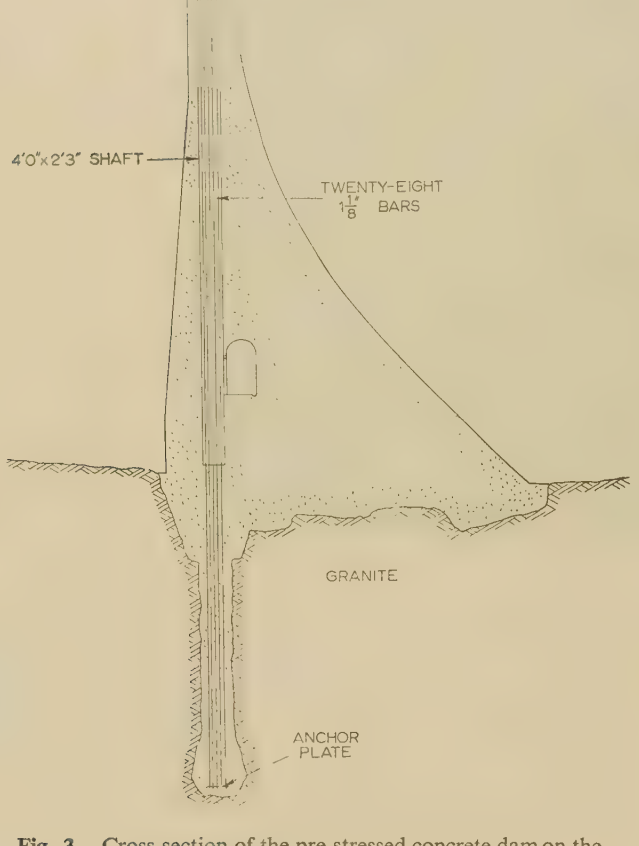


Fig. 3.—Cross-section of the pre-stressed concrete dam on the Allt-na-Lairige, Glen Fyne.

Tunnelling is now carried on by lightweight drills, originally perfected in Sweden, which can be handled by one man and rates of driving frequently exceed 200 ft/week; in three cases, in tunnels of about 10 ft diameter, more than 400 ft have been driven in a week, the present record being 444 ft. The accuracy of tunnel-driving is a matter of professional skill which members of The Institution can well visualize for themselves; the way in which the engineers light-heartedly start boring from both ends and invariably meet in the middle warrants a tribute of admiration. It was not always so.

There is an apocryphal story that, when the citizens of Carthage wished to drive a tunnel to bring in a new water supply, they started from both ends and the time came when the men working at each tunnel face could hear the muffled hammering of the men at the other face. Excitement rose, but as time passed, the noises grew fainter again and they ended with two tunnels instead of one.

We are on firmer ground, however, with the story of another classical engineer who was more successful. Herodotus relates that the Greek engineer Eupalinus in the sixth century B.C. organized large water supplies; he drove a tunnel 4 240 ft through limestone rock to supply the town of Samos. The tunnel was 8 ft square and was driven from both ends. When the two headings met, the error was only one yard.

Another tunneller was King Hezekiah who, according to 2 Kings, chapter XX, verse 20, and 2 Chronicles, chapter XXXII verse 30, constructed an aqueduct from the River Gihon. It le to the pool of Siloam and is still in existence, and according to Hebrew inscription, it was driven from both ends; they were no quite meeting but they were very close; the workmen in eac heading could hear the others and they drove a short traverse an joined up successfully.

(2.4) Power Station Buildings

Power-station styles have not been stereotyped. Those a Sloy, Pitlochry and Clunie (Fig. 4) are of classical style and face with reconstituted Aberdeen granite. Those at Affric an Grudie Bridge, Glascarnoch, Luichart and Tor Achilty, furthe north, have been built by local masons of sandstone from loca quarries, three golden yellow and two red, while at Kirkwa native whinstone has been used to build a Diesel generatin station. The smaller hydro-electric stations for local supply i the remoter Western Highlands have a rural simplicity, stee pitched roofs, and a finish of rough local stone or whitewashe roughcast. There are underground stations at Shira on Loc Fyne, St. Fillans and at Ceannacroc and Dundreggan in Gle Moriston.

(2.5) Control of Water

Rainfall is heavy in the Highlands. It varies from abou 40 in in the east to 140 in in the west in an average year, and con ditions vary widely from day to day, week to week, and month t month. Occasionally, a whole month may pass with hardly an rain, or there may be a deficiency of 50% over a 3- or 4-mont period; on the other hand, heavy rainfall has been experience varying from 3 in to 8·9 in in four days over the whole stretc of the Western Highlands from Sloy on Loch Lomond t Loch Fannich in Ross-shire, while on one occasion in a smal area at the head of Loch Quoich, 10 in fell in 22 hours. Com drought or come flood, the demand for electricity must be met and consequently the dams are built to store very substantia quantities of water ranging from about 20% to 60% of a year' rainfall. This storing of water also helps considerably to reduc the damage due to flooding lower down the glens and straths.

Different countries have different storage problems. I countries like Canada, Scandinavia, and Switzerland, severe an prolonged freezing weather in winter creates the need for a hig percentage of storage, not so much because of ice on the reservoir as because run-off from the catchment areas dwindles almost t nothing. In hot countries, on the other hand, an increase in th level of a lake may involve a large increase in surface area an correspondingly greater losses due to evaporation. In th Highlands the variation in *average* run off between winter an summer corresponds quite closely with the variation in electrica load, and this helps to offset the disadvantage of smaller rive systems and makes the water power of the Highlands particularl suitable for general public supply (Fig. 5).

The statement that the seasonal variation in run-off corresponds with the seasonal variation in electrical load might seem to b contradicted by the extremes of high and low rainfall mentione earlier in this Section. Experience shows, however, that althoug rainfall may vary enormously from month to month, these larg short-term variations are considerably smoothed off in the cours of the calendar year. Taking average figures for Scotland as a whole, rainfall has not since 1881 fallen below 80% of averag or risen above 129% of average in any one year. It would no do to assume that the figures for individual catchments in th Highlands show such small divergence, as there have indeed bee occasional individual deficiencies of 30% or thereby; but wit the aid of reservoir storage plus the flexible use of steam powe

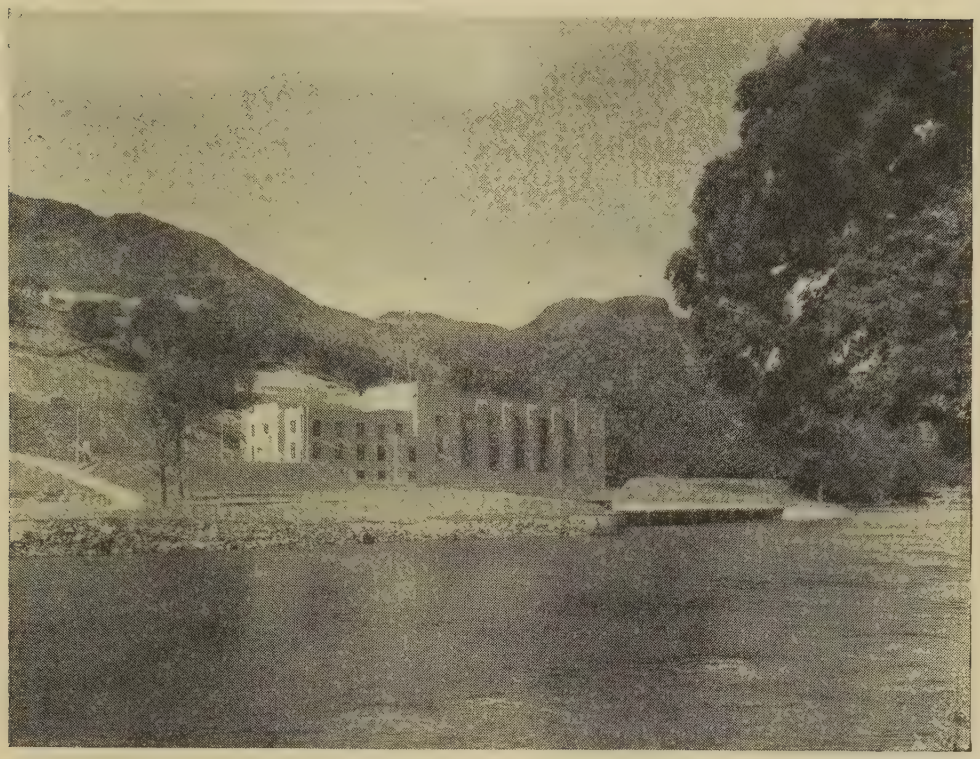


Fig. 4.—Clunie power station (Perthshire).

hey can be reasonably well overcome. The relationship between ainfall and run-off is too specialized for discussion here, but the wo have a fairly close resemblance.

(2.6) Water Turbines and Electrical Generators and Plant

Hydraulic conditions vary widely, because the production of a hydro-electric scheme is related both to the volume of water available and to the head through which it is developed. Consequently, water turbines and water turbo-alternators are much less standardized as to size and speed than steam turbines or Diesel engines. The extremes of design which have so far been adopted in the Hydro-Electric Board's scheme are as follows:

The highest individual turbine output is 40 000 kW, produced by a vertical Francis turbine and alternator in the Clachan power station of the Shira Scheme on Loch Fyne. The gross head of water on this machine is 960 ft and it runs at 428 r.p.m.

The maximum head employed is 1 362 ft in the Lawers Scheme, where the power station contains one 30 000 kW 375 r.p.m. horizontal-shaft alternator driven by double overhung Pelton wheels.

At Invergarry power station there is a 20 000 kW 250 r.p.m. vertical-shaft Kaplan turbine operating under the unusually high head of 175 ft.

Transformers and switchgear are of standard types, but a word should be said about transmission. In the Highland Grid, transmission is outwards to the north, east, and south from hydro-electric stations, as these are mainly in the central and western mountains. The most interesting Grid line runs from Fort Augustus across the Corrieyairack Pass at a maximum height of 2 507 ft on the route of General Wade's road between Dalwhinnie and Fort Augustus, and rather unexpectedly, there is a 132 kV line from Beauly to Caithness in the far north with a 33 kV connection reaching as far as John o' Groats where, during the severe snowstorms of February, 1955, a linesman and transformer were dropped by helicopter. The next interesting development is expected to be a line at 275 kV from Beauly to Kintore in Aberdeenshire to supply the growing agricultural and industrial demands of the north-east of Scotland.

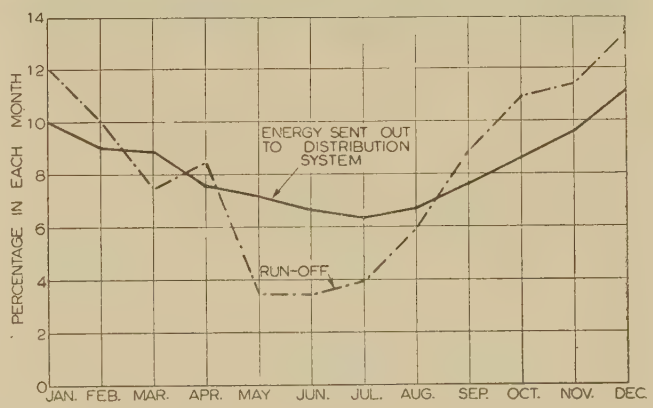


Fig. 5.—A comparison of the variation of load and the variation of run-off of rainfall.

(2.7) Production of Hydro-Electric Power

The Hydro-Electric Board has been in existence for 12 years. During the first six years surveying and construction were under way; the first schemes were set to work in 1950 and progress can be summarized as follows:

	1949 (Pre-war Grampian stations, etc.)	1950 (First year of new schemes)	1955/56 (Estimated)
Capacity, kW	87 000	285 000	634 000
Energy generated per annum, kWh × 10^6	322	522	1 620

The rate of water-power production in 1955–56—in terms which are easily understood—is equivalent to about 960 000 tons of coal per annum, or over a fortnight's production of the Scottish coal pits. If regarded as a saving of imported coal at £6 per ton, it will represent a dividend to the country of

£5 760 000 per annum of foreign currency. When the schemes now under construction and survey are operating—say in another ten years—the production will double the 1955–56 figures, being about 1 300 000 kW and 3 600 million kWh per annum, and beyond that the total potential capacity of the Area—not all of it economic by present-day standards—might treble that again. The river systems which have considerable power resources harnessed or being built or surveyed are:

River system	Capacity in operation, and under construction and survey kW	Energy per annum kWh × 10^6
Tay (including Tummel and Lyon and Earn)	392 000	1 133
Ness (including Garry and Moriston)	109 000	376
Conon (Ross-shire)	107 000	435
Beauly (including Affric and Farrar)	133 000	471
Findhorn	150 000	500

Mention must also be made of the small schemes for supplies in remote areas. They include water-power schemes to supply Ullapool and Lochinver, Gairloch and Aultbea, Lochalsh, Skye, Morar, Kintyre and Bute, while, in addition, Diesel-engine generators supply Arran, Islay, Lewis and South Uist in the Outer Hebrides, the Orkney and Shetland Islands and the County of Caithness. These small local schemes are collectively of great value in bringing modern amenities to isolated places.

(2.8) Amenity

It is sometimes feared that the results of all these hydro-electric schemes will be that rivers will disappear from the Highlands and only dried-up river beds will be left. There are one or two cases of dried-up river beds, dating from the 1920's before the days of the Hydro-Electric Board when roads were poor and tourists fewer and people cared less about these things, but nowadays compensation water is almost always considerably more than the summer dry-weather flow. In addition, many amenities have been improved. The old "Road to the Isles" along Loch Tummel, for example, has been made suitable for motor traffic; the road up Strathglass and Glen Affric has been rebuilt, and an independent authority—the Council for the Preservation of Rural Scotland—says that the prospect up Glen Affric has been improved by some 100%. Finally, the great amenity of electricity in the home, the croft and the farm has been brought to tens of thousands of dwellers in the countryside and the remote glens and islands and that is, without doubt, the greatest contribution to amenity which the Board have made.

(3) DISTRIBUTION OF ELECTRICITY

When the Hydro-Electric Board became responsible for electricity distribution in their present Area in 1948, the larger towns such as Aberdeen, Dundee, Perth and Inverness, were already supplied, and so were the towns and most of the larger villages of the north-east coastal strip. The number of people who were still without a supply, however, was about 600 000, or just one-half of the total population of the area, and the great majority were widely scattered in the sparsely populated country districts. Only one farm in 14 and one croft in 100 were connected to the mains, whereas the proportion in the rest of England and Scotland was nearly one farm in three. There was therefore much leeway to catch up, but the task was important because the Area not only produces but also exports food on a large scale. Agriculture, the oldest and most important industry in the world, is also by far the most important industry in the area. Now, at the middle of 1955, the stage has been reached when two-thirds of those 600 000 who were still waiting for a supply have been connected to the mains. The proportion of farms and crofts connected u has risen to 45%, and this progress has been spread from th Island of Lewis in the west to the good farmland of Aberdeen shire in the east and from the Peninsula of Kintyre in the sout to Shetland in the north. Obviously, the most difficult part o the task still remains to be done, because the people who hav still to be connected to the mains live in the remoter parts of th countryside which are more costly to reach. Nevertheless, large programme of work on comprehensive rural distributio schemes is already in hand, and before the end of the preser decade should bring the number of farms and farm-worker cottages on supply up to 75 or 80%. The importance of th development can hardly be exaggerated. Electricity is worth a extra hand about the steading for the farmer; it is worth a pa of hands for the farmer's wife in the home, and it is becoming a essential requirement for farmworkers' cottages to encourag them and their wives to stay on the land. The growth of deman in the country districts has been remarkable: farming deman increased by 35% during the year 1953–54—and in the whole o the Board's Area, including the towns and cities, the increas between 1947 and 1954 has been 225%.

(4) ECONOMIC DEVELOPMENT AND SOCIAL IMPROVEMENT OF THE BOARD'S AREA

The direct effect of the Board's activities on their Area is t provide work, to help agriculture and industry, to improv amenities in the home, and to market water-power—one of th great resources of the Highlands—for the benefit of the Area.

Developments, however, have also been encouraged in number of other directions, examples of which are mentione in Sections 4.1–4.5.

(4.1) Building in Stone

Practically all the Board's power stations and about 85 sta houses are being built in stone. For power stations and oth large buildings, the cost has been sometimes a little cheaper an sometimes dearer than building in reinforced concrete, whi houses at this early stage have also been somewhat dearer. Th great advantages, however, have been the improved appearan of the buildings, the durability of the houses and, above all, th fact that a native industry is being encouraged. Work is provide for local masons and quarrymen and the money is all spent an circulated locally, a far better alternative than buying importe bricks and other scarce building materials, which would simp lead to greater depopulation of the North.

(4.2) Gas Turbines and Peat

A 10 000 kW gas turbine of the closed-cycle type is being install at Dundee. It is similar to one which is being installed in Pa and is unique in Great Britain. It will run on oil. This i expensive, but it has paved the way to running a similar type turbine on pulverized peat, and on coal. If success can achieved in the economic combustion of peat, it will indeed be great importance to the Highlands. The difficulties are co siderable, principally because peat in its natural state contai 90% (or more) of water and only 10% (or less) of solid com bustible material. The technical problems of pulverizing an burning the peat once it has been dried, however, have alrea been largely overcome, and a 2 000 kW turbine is being built f installation on a peat bog at Altnabreac in Caithness. When t difficulties of winning and drying the peat are also overcome, t way will be opened not only to the use of peat for power produ tion, but to the uncovering of many acres which are now of lit value for farmland or afforestation.

(4.3) Wind Power

The Board have an experimental 100 kW wind-driven generator Costa Head in Orkney which has already worked and enerated electricity, although not yet on a commercial basis. he problems of building a machine which will not only operate tisfactorily in winds of moderate strength but will stand in gales f hurricane force are not easy to solve.

(4.4) Grass and Hay Drying

Experiments in electrical grass and hay drying have been arried on for some years and promising results have been btained on farms and crofts in various parts of the Board's rea. Owing to humidity it is necessary to heat the air which is lown through the hay, and the cost of the treatment amounts to bout £12 per ton. The enhanced value of the dried grass or ay, however, justifies this expense, the protein content being ncreased usually from about 6% to about 11%. One of the est reports which the Board have received reads as follows:

> One of the crofters reported that he had a cow which had doubled its milk yield being fed exclusively on electrically dried hay. He would not concede that all this 100% increase could be due to dried hay; he preferred to leave it as a "phenomenon he cannot understand."

(4.5) New Industries

Hydro-electricity benefits the North of Scotland, but the ndustrial lowlands also have a stake in this enterprise. They are ontributing much of the material and equipment for the Board's levelopments. Encouraged by the Hydro-Electric Board, a new ndustry—that of the building of large water-turbines and elec-rical generators—has been brought to Clydeside. This industry, which started by supplying the requirements of the Board, has expanded until it is now building on a large scale for export. A wide variety of hydraulic machinery, cranes, cableways, transformers and electrical machinery is being made in Edinburgh, Dundee, Aberdeen, Kilmarnock and other places.

In short, the Board is doing its best by the provision of work, the development of agriculture and the increase of manufactures to help to stem depopulation and to lay a foundation upon which prosperity can be built.

(5) PEAK LOAD POWER

Three-quarters of the hydro-electric power produced by the Board is consumed in its own supply area at about average load factor, and a quarter is exported to South Scotland as peak load, the present supply being 215 000 kW at a load factor of about 15%. Water power is well adapted for peak-load supplies, because it can be switched on or off at the turn of a tap and because the capital cost does not increase much with increased plant capacity, no extra expenditure being required at the dam, and the extra cost of a larger tunnel being relatively low.

Full advantage was taken of these facts in the Board's first large scheme, the Sloy Scheme, which is situated near Loch Lomond, less than 40 miles from industrial Clydeside, and has a capacity of 130 000 kW at a load factor of about 10% (Fig. 6). Another peak-load station is Errochty, part of the Tummel–Garry Scheme in Central Perthshire, with a capacity of 75 000 kW, also at about 10% load factor.

Eleven years ago, when these schemes were being considered, it was thought that further peak-load development would only be gradual. The recent prospect of rapid nuclear power development, however, arising from the recent Government decisions and the desirability of running modern high-pressure high-temperature steam stations at loads as steady as practicable, bring the peak-load question into new prominence, and seem likely to call for pumped-storage peak-load schemes on a substantial scale.

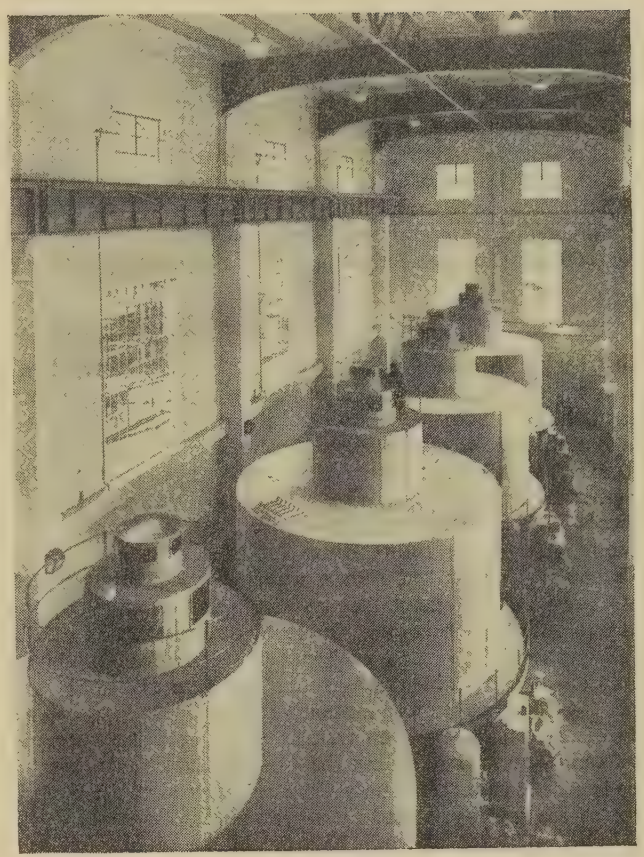


Fig. 6.—Sloy power station—four 32 500 kW vertical-shaft machines.

(6) PUMPED STORAGE

The basis of pumped storage is that at night, when demand for power is low, water is pumped from a low-level reservoir to a high-level reservoir and during the day it is allowed to flow back, producing power when most needed at times of peak load.

(6.1) Past and Present Schemes

The Board is already installing an experimental 5 000 kW pump in the upper Shira power station, so that in wet weather surplus water can be pumped back from the lower dam into the main reservoir, and the Central Electricity Authority are including a 300 MW pumped-storage scheme in their Welsh Hydro-Electric Scheme.

Some pumped-storage schemes have been in operation in Europe since the 1930's, and one is being built in Canada at the Niagara Falls to harness more power at night which would otherwise go over the Falls, as there is no storage in the river.

Attempts were made in 1935 and 1936 to promote the Sloy Scheme as a pumped-storage scheme, but they did not succeed, and when it came to be promoted by the Hydro-Electric Board in 1944, although pumping was considered, the alternative of bringing in additional water by aqueduct from neighbouring catchments was adopted.

(6.2) Future Schemes

Pumped-storage schemes are economic in conjunction with coal-fired power stations because they provide peak power at low capital cost and enable the steam stations to be operated more

economically at a steady load; with the development of nuclear power-stations, which apparently have to run at a steady load by day and night, pumped storage may be of value on a very large scale.

It is estimated, in the recent White Paper, that 10 000–15 000 MW of nuclear power and 2 000–4 000 MW of hydro-electric power and pumped-storage power may be commissioned by 1975, and the possibilities which are considerable in the Highlands are being examined. In addition to the normal development of water power, it may be desirable to develop up to 2 000 MW of pumped-storage in the years between about 1961 and 1975. Suitable sites are more prevalent in the Highlands than elsewhere, so that even 2 000 MW might be only a first stage with considerably greater developments to follow in the remoter future. Loch Sloy itself would provide a suitable and economical site; new tunnels and reversible pumping stations would be required, but the dam already exists and on that scheme alone it would be technically possible to develop 2 000 MW. So large a development would naturally present a number of problems, and if so much power were to be developed there, it would presumably be done in stages, coupled with the appropriate development of transmission.

DISCUSSION BEFORE THE INSTITUTION, 5TH JANUARY, 1956

Sir Charles Westlake: It is a sad thing that Mr. Lawrie is not here to-night. Behind the factual statements in the paper there emerges the character of the man. In this paper—I think it is almost unknown for such a thing to occur in an Institution paper—there is a touch of humour. Mr. Lawrie was much more than an electrical engineer. He believed in electricity as a great social service and he was determined to see the benefits of power taken to the remote areas in the North of Scotland.

He had to face, as Mr. Fulton will have to face, severe economic problems; the more they try to get to the outlying parts, the more difficult it becomes. In 1929, in a very much smaller way, I had to face the same problems in Dumfriesshire, where a population of only 60 000 was spread over an extremely wide area. At that time we had a remarkable County Clerk. I was quite orthodox, having been trained to demand the guarantee fees from every consumer, but the County Clerk said: 'No. If there is a deficit on the County Council undertaking, it must be borne by the ratepayers, and therefore the ratepayers must get a supply of electricity, wherever they are in the county, and with no guarantee whatever.'

I was shocked, but I have lived to applaud that decision. My successor in Dumfriesshire, Mr. J. S. Pickles, who made such a brilliant success of the job, found that, from the commencement of supply to the time he was 'elevated' never was a loss experienced.

The paper covers a long period of development—over 170 years—but I enjoyed, among other things, the brief description of how the story began in the North of Scotland, and I have often felt that the early days of public supply in this country have never been properly recorded. Those who have reached maturity in the supply industry have missed the many fascinating stories which pioneers of our industry could have told.

The North of Scotland Board has been fortunate in the leaders it has had. In the days when controversy raged over the country and there were cries of the desecration of the countryside, they had a difficult problem, but they saw the need for the preservation of the salmon, as we have already heard. There must have been a fisherman on the Board. Certainly I know from experience that the Electricity Commissioners had a warm sympathy for the people there. The Commissioners not only desired the development of electricity supplies but were interested in Scotland for its own sake and for the preservation of its natural beauty. I refer to Lord Hurcomb and the late Sir John Kennedy. I gather that the controversy has now practically ceased and that tourists find that the work of the North of Scotland Board has created new beauties.

I was interested to read about the salmon leap. During the construction of the Owen Falls dam, the supply of water had to be limited at Ripon Falls, and the fish in the turbulent water were as thick as sardines in a tin. The inference has been drawn that this barrier, which has been flooded since the completion of the Owen Falls dam works, has prevented fish from ever passing from the Nile into the lake, and my successor, Mr. Fenton, may have to face the problem of getting fish over the dam.

Water control is a fascinating subject, but it is a topic which never gave the slightest anxiety in Uganda. With an area of some 30 000 square miles in Lake Victoria, it seems that the question of supplies of water will never be a problem.

Mr. T. G. N. Haldane: Much of the energy produced from the hydro-electric developments in the North of Scotland is now required for local consumption, but the remainder can, as experience has shown, be accepted at very low load-factor by the industrial South with less difficulty than at one time appeared likely. Broadly speaking, it is generally advantageous to develop hydro-electric power at the lowest possible load factor, and hydro-electric plant is the most efficient means of meeting peak loads.

As the North of Scotland system develops, it will become increasingly necessary to achieve maximum integration of hydro-electric and thermal power. One important way of achieving this integration is by means of pumped-storage schemes, for which exceptionally suitable sites are available in the vicinity of Loch Awe and Loch Lomond. Special advantage accrues from superimposing pumped-storage on ordinary hydro-electric schemes, where both top and bottom reservoirs will be available and where penstock costs will be incremental.

Further valuable integration can be obtained by the provision of a relatively small amount of pumping capacity wherever this is possible. Such plant will be used to maintain reservoir levels rather than to operate on a pumped-storage cycle. Pumping plant used in this manner has other incidental advantages including increased flexibility in the operation of ordinary hydro-electric schemes. In general, the closest possible integration of thermal and hydro-electric plant is very advantageous to both thermal and hydro engineering.

Mr. J. D. Peattie: In the 1943 Act the Hydro-Electric Board were made responsible for the generation of electricity by water power or other means. Their primary duty is to provide supplies of electricity to ordinary consumers. A secondary duty is to supply electricity to the Central Authority.

The duty of the Central Authority is somewhat different. They are called upon to develop and maintain an efficient, co-ordinated and economical supply of electricity within their own area and for that purpose to generate or require supplies of electricity. In part the supplies required come from the Hydro-Electric Board.

The duties imposed by Parliament call for compromise by engineers working out details.

The conception of load factor applied to generation requires examination. The amount of coal which can be economically used at a given site is fixed in much the same way as the energy which is available from a catchment area.

In this country the total amount of all interconnected plant is, after allowance for availability, equal to the total load. It

oubtful whether in fact this is the best solution to the problem. may be that in some cases extra output capacity could with dvantage be installed.

This posthumous paper adds another chapter to the history of cottish hydro-electric power development. It is a proud record nged with sadness so far as The Institution is concerned.

The monuments to the work of the pioneers are scattered over cotland where the people's savings have been transformed into ssets fashioned by local craftsmen. The value of these assets ill remain despite the relentless advance of inflation, and the nen and women of the islands and glens have now offered to hem those gifts which a supply of electricity can bring.

The Rt. Hon. Lord Hurcomb: I am glad to have the opportunity of intervening in this discussion upon an aspect of hydro-lectric schemes which is probably very rarely, if ever, brought o your mind and which arises directly out of the paper. I nave always been interested in the problem of the conservation of Nature, and naturalists throughout the world have become ncreasingly disturbed at the immense loss and destruction of areas and of life of great biological interest through interference with the regime of rivers—what is called correction, including canalization and revetments of the banks—and through the construction of dams, usually, although not always wholly, for the purposes of generating electricity.

I will not take up time in dealing with what are called the amenity questions, because I take the view that, given proper care, many of the schemes can add to the beauty of the scene, considered merely as landscape. That has been well recognized in Scotland, and it can be said of some schemes abroad that the landscape has not only not suffered but has often been improved.

Nor will I take up time with the very important and interesting question of dealing with migratory fish. That, again, is well understood here, and I am always proud to think that the North of Scotland Hydro-Electric Board has led the way to a solution of that problem.

But those are aspects which are easily understood—aspects in which I think it is fair to say that the North of Scotland Hydro-Electric Board has set an example which is appreciated and which has been of great help to me in discussions with some of my foreign colleagues in the International Union for the Protection of Nature, to whose work I should like to refer in a moment.

What is disturbing to naturalists is the much wider question of the interference with Nature, not in the sense of one or two particular creatures or plants but with Nature in its wider sense. Nature does not consist of a few creatures or plants existing in isolation from one another, but of an immensely complex association of all sorts of plant life and animals, vertebrate and invertebrate, closely related to the soil and intimately connected with one another; and the naturalist does not want to see all that obliterated. I need not go into the reasons for that; I must ask you to take it that the opportunity of studying those forms of life and that association are of immense importance and interest to naturalists everywhere.

The International Union for the Protection of Nature has devoted a great deal of time to these problems. Two or three years ago there was a meeting in Caracas, Venezuela, when a long series of papers on the subject was read. I have had the honour of editing these for the Union and they have now been published. It would interest many of you to look at them. They include some papers by eminent engineers, particularly one by Semenza, an Italian engineer known to many of you.

Until recently I think it has generally been true to say—and I hope you will take no offence if I put it this way—that the engineer has been not very sensitive even to the claims of amenity and landscape unless he has had them forced upon him. The reasons are obvious. He is thinking mainly of technical difficulties and economy. He has not been sensitive at all to the biological consequences of what he does.

On the other hand, some of the naturalists have gone to the other extreme, making insufficient allowance for the economic and technical necessities of the scheme; they may have seemed impractical to you. That is not the position of the Union at all. There are very few schemes to which it has felt it necessary to object out-and-out, although there have been some. The classic instance is that of the Swiss National Park in the Lower Engadine—an area of unique interest to naturalists because it is almost the only part of Europe which, broadly speaking, has not suffered the interference of man for centuries. It was set aside for that very reason by a public Act of the Swiss Government. A fight is now going on between those who want it to be used as an area for the development of electricity and those who want to keep it as a unique area in Europe.

That apart, you may take it that naturalists, and certainly the Union with which I am connected, wants to be practical, and what we have argued is that it should be possible to avoid or mitigate a great deal of the biological loss which arises from the construction of hydro-electric schemes by proper consultation at the right stage between the engineer and the biologist. That is a policy which I have strongly urged upon my colleagues, and I have found support for it in the action of the North of Scotland Hydro-Electric Board.

First of all, in that case our law has provided for an Amenity and a Fisheries Committee. Secondly, the Board had the good sense to use, as their public relations officer and adviser in these matters, a biologist of distinction, Dr. John Berry, who recently read to the Glasgow Philosophical Society a paper on the theme which I am putting forward.

They found, in constructing one scheme, that a very rare species of rush—not a very exciting plant, but in fact it has been found only at that spot—was growing on the side of a slope which they intended to submerge; and the Board reconstructed the habitat of that plant further up the hillside.

This very useful example of enlightened action has gone all round the world among naturalists as the kind of thing which the promoters of hydro-electric schemes ought to be prepared to do. I do not see why it should not be done. The policy which I should like to see adopted by all organizations and authorities charged with the development of hydro-electricity is that of employing as adviser an independent biologist of standing who could make a comprehensive survey of all the alternative schemes and point out beforehand what are likely to be the biological consequences of various courses of action. Although he could not always have what he wished, he would, I am sure, be able to secure compromise action in many directions which would be of very great value.

The sort of interference which can cause serious biological damage is very well described by Dr. Berry in the paper which I have mentioned. First of all, there is the diversion of water from one natural catchment basin to another. If there is a marked chemical difference between the waters, the results may be quite disastrous. There are all the alterations in the run-off and water-table, both above and below the dam, which can have profound results.

Not all the consequences are necessarily adverse. From the point of view of my particular interest in bird life, to say nothing of being a fisherman, the construction of a new reservoir may provide new habitats of great interest. Broadly speaking, however, the biological consequences of your constructions can be serious, and I think it should be accepted policy on the part of engineers to take biologists into consultation at the earliest possible stage. It is no use bringing them in afterwards or, as

some people would say, hiring a specialist in order to support what has already been decided.

The International Union is meeting in Great Britain for the first time at Edinburgh, in June, and many of them are very much interested in seeing what has been done in Scotland, not only in the matter of fish passes but generally in this connection. We shall indeed have much to show.

I can only deplore that Mr. Lawrie himself will no longer be there to show them round. We had his sympathy and I know we have that of Tom Johnston. I am sure my friends will get every help and assistance from Mr. Fulton.

The questions to which I have referred are part of a very big issue. The whole face of the world, let alone that of this country, is changing almost under our eyes. Natural life of immense interest is being obliterated or lost in many directions. I am sure that you, as scientific people, can come to some accommodation with the biological sciences and do something to meet their point of view. I do not suggest that this is a very grave issue in this country, but it is so in many parts of the world, in fact in almost every part of the world, including Central Europe. I am glad to think that we have in the North of Scotland a good example of how these matters can be intelligently and wisely tackled.

Mr. R. W. Mountain: In Section 2.5 we are given average rainfall figures and the variations from the average in different years. I wonder whether Mr. Fulton would be able to tell us the effect or the consequences of the drought which occurred in Scotland last year. Taking one year with another, I imagine that these difficulties arising from shortage of water are to be expected and are part of the balance of the economy of hydro-electric schemes in Scotland.

In Section 2.6 there is a reference to a vertical-shaft Kaplan turbine at the Invergarry station. I was hoping to be able to say that it had been put into commission, but I gather that a few more days may elapse before the set is actually commissioned. It would have been appropriate if I had been able to make that announcement.

In Section 3 a point arises to which Mr. Peattie has referred in a slightly different context. I wonder whether Mr. Fulton could tell us what is the capital expenditure of meeting these rural supplies in the North of Scotland, per consumer. It may not be possible for him to give the figure at the moment, but perhaps he could give, roughly, the percentage of it which is, in effect, a subsidy of that supply.

Turning to pumped-storage schemes, I imagine reference will be made to the Festiniog scheme, mentioned in Section 6, but an important scheme from the point of view of the Hydro-Electric Board is the Sloy scheme, also mentioned. I gather that the proposal may be for a first installation of 600 MW, and the possibility has been explored of pumping units perhaps of 100, 125 or 150 MW—i.e. 3-machine units: a pump, a turbine and a combined motor-generator.

I should like to pay my personal tribute to the inventive genius of Sir Edward MacColl, the first executive officer, and to the integrity of Mr. Lawrie, his successor, who carried on the same high tradition.

Mr. M. Braikevitch: Would Mr. Fulton please say under what head the pump-storage he refers to will be developed?

The 5 MW horizontal-shaft pump-storage unit the Board already has consists of a turbine, a generator and a pump. A unit of similar type, but very much larger, would usually have a vertical shaft so that turbine and pump may be drowned to avoid cavitation, and the generator may be placed at a higher level. The pump and turbine are designed independently for maximum efficiency, which is important for 'daily cycle' operation.

Since, theoretically, both pump and turbine are reversible, can they be combined into a single machine? Intensive research has been undertaken to answer this question. The turbine deals with the head in a single stage and is therefore simpler than

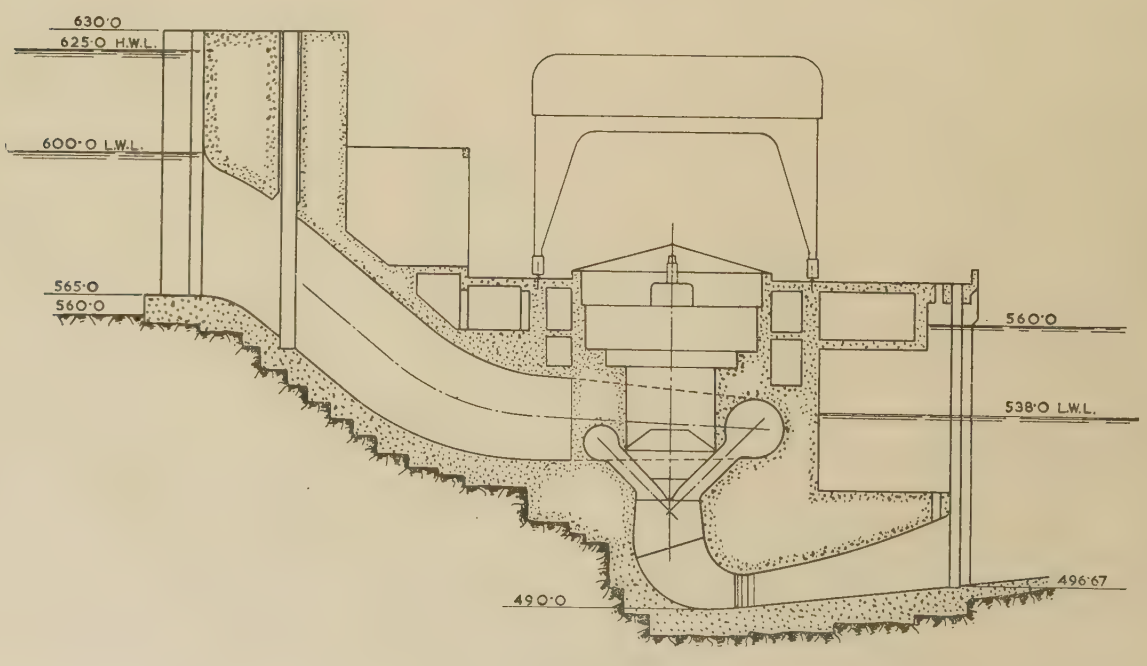


Fig. A

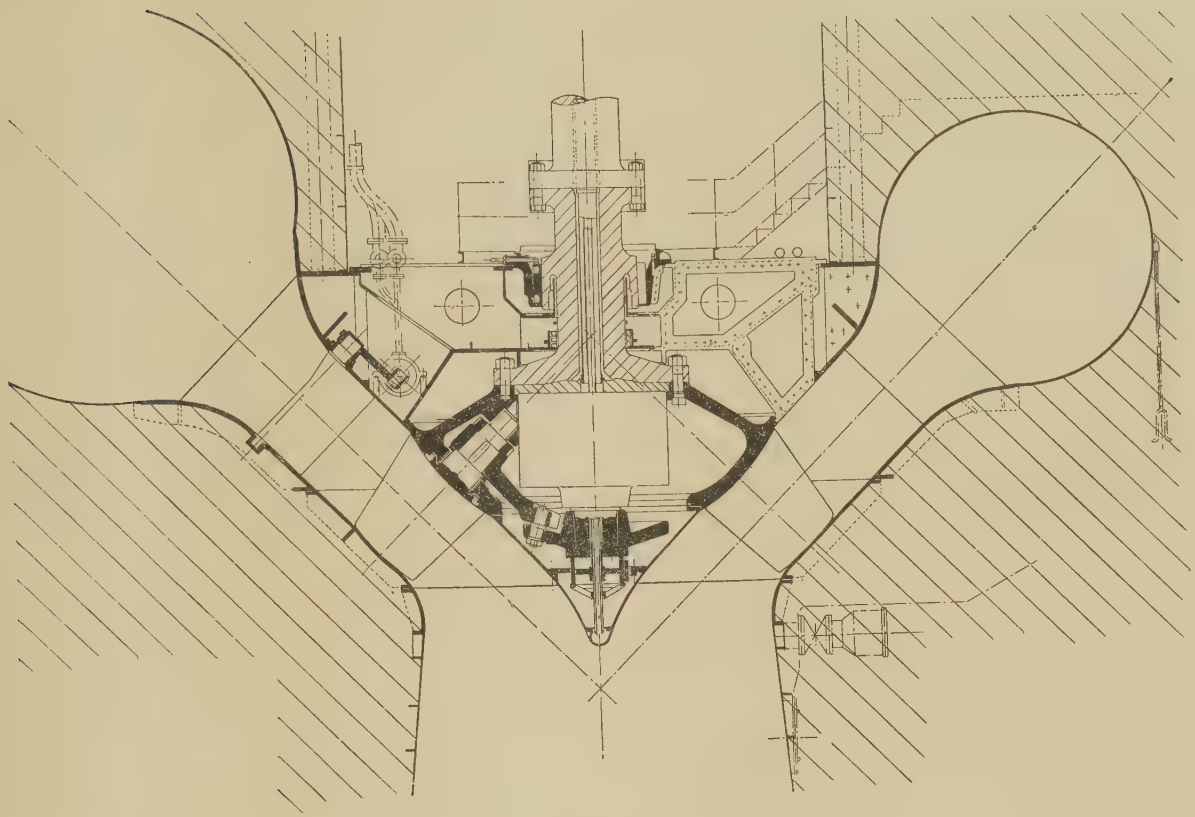


Fig. B

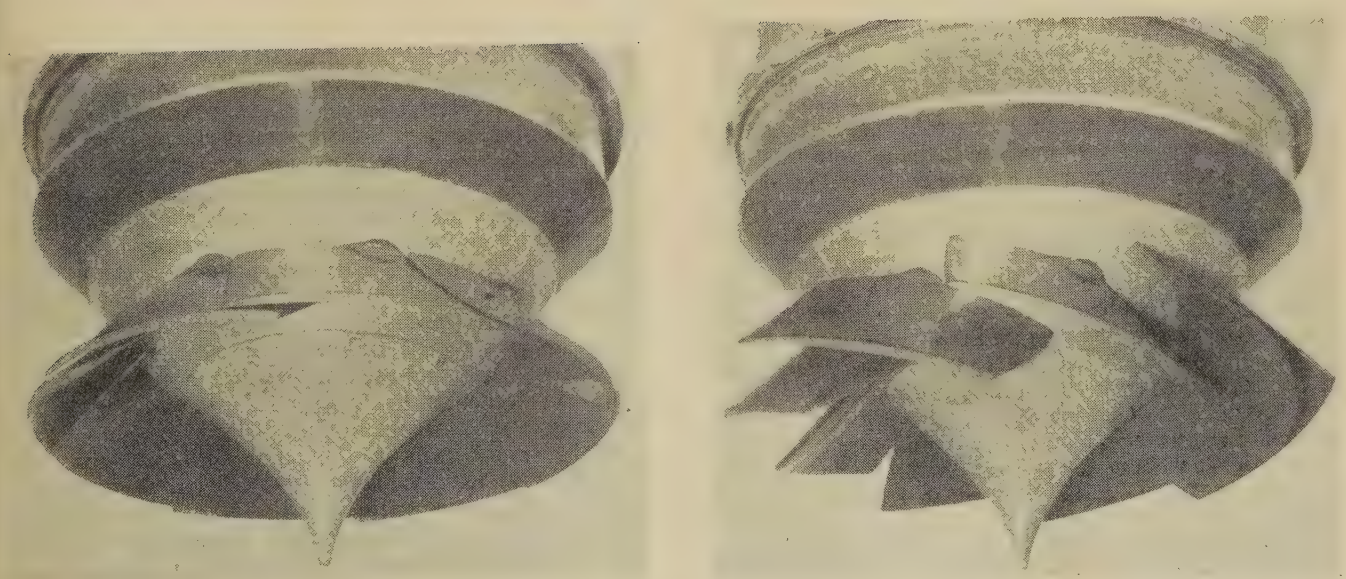


Fig. C

the multi-stage pump. The reversible machine should therefore preferably be single-stage, the more so since quantitative regulation is desirable for the turbine, meaning either movable guide vanes or movable runner vanes. The very low pump setting will have to be retained for the reversible machine.

The Niagara pump-storage scheme was mentioned in the paper. The head is 50–90 ft, and here reversible pump-turbines invented, designed, and tested in the laboratory under full prototype head—all in this country—are actually being used. Fig. A shows a section of the power station. The six units are of 46 000 b.h.p. each, and the runner is of about 21 ft diameter. Owing to the physical dimensions resulting from the low head it would have been quite uneconomic to put in units with separate pump and turbine.

Fig. B is a cross-section of the machine, which is in fact a Francis turbine with movable runner-vanes operated by a servo motor containing a rotor coaxial with the main shaft and coupled to the vanes. The gear is located inside the runner hub.

To guard against cavitation the runner is submerged—16 ft or more. When starting as a pump, the motor-generator has to rotate the wheel in water, and this would mean a very high torque at low speed—a difficult proposition electrically. The movable runner vanes solve the problem as will be seen from Fig. C, which shows the runner vanes in both the open and the closed positions.

When closed at the beginning of operations the vanes form a reasonably smooth cone easily moved through the water so that large torque is unnecessary.

At speed the vanes are opened and pumping commences. By adjusting the vane opening, the quantity pumped efficiently at any given head can be varied. When the turbine is running, the runner vanes vary the quantity of flow in accordance with the load demand. A unit of this type could probably deal with a head of 300 ft or more.

Mr. J. Guthrie Brown: I knew Mr. Lawrie for about 30 years and I would like to be associated with previous speakers in their expressions of regret at his untimely death.

I propose to make a few comments on the very high architectural standard adopted by the North of Scotland Hydro-Electric Board in their power stations. During last year I visited Australia, Tasmania and New Zealand and saw many of the hydro-electric schemes in these countries. I am therefore able to make a comparison between the stations in Scotland and those oversea.

At Pitlochry, Errochty and Grudie Bridge—three typical Scottish stations—the appearance in each case is excellent. The power-station walls, of masonry, or reconstructed granite in the case of Pitlochry, are very much in harmony with the Scottish scene. The transformers and electrical equipment are discreetly hidden behind the stations.

In New Zealand, the two principal stations are Maraetai in the North Island (180 000 kW) and Roxburgh, at present under construction, in the South Island (320 000 kW). While great care has been given to the architectural treatment of the concrete walls of the power station, the appearance of transformers and electrical equipment closely adjacent to the power-station walls, or on the roof of the power station itself, is distracting.

In Australia, the Guthega Station (60 000 kW) of the Snowy Mountains Project, opened in 1955, has walls constructed in plain *in situ* concrete without any external architectural treatment.

Finally, in Tasmania, the Tungatinah Station (125 000 kW), opened in 1955, is of interest. The external appearance of the station is very pleasing, despite the fact that the walls are of corrugated sheeting.

Mr. J. M. Ferguson: Besides being of the utmost importance to the economy of Scotland, the co-operation of the North of Scotland Hydro-Electric Board has been of great benefit to British manufacturers. The experience gained on their system has been of direct benefit in obtaining contracts in Europe, in the East, in the Dominions and in America.

There is no reference in the paper to training. It is often extremely difficult to get skilled staff to operate in the remote stations, and it would be interesting to know whether this difficulty is likely to bring about an even greater degree of remote control than is used at present. When the Galloway system was initiated, remote control was borne in mind. Two of the more remote stations, Earlstoun and Carsfad, were run up automatically and synchronized over pilots from Glenlee, with the water-intake gates remote controlled from the nearest stations.

Subsequently a number of the smaller stations on the North of Scotland hydro-electric system have local pushbutton starting with automatic synchronization, such as Gaur.

Will Mr. Fulton indicate whether there may be an even greater tendency to go over to automatic control in the future?

In Sweden considerable experience has been obtained on a useful d.c. transmission scheme supplying the island of Götland from the mainland. Is there any scope economically for such a scheme, probably on a reduced scale, for the supply of power to the Islands?

On the subject of hay drying, have the Hydro-Electric Board considered the possibility of high-frequency drying? This would require much more complex equipment with increased capital cost, which would be suitable for use only in a drying centre, but two possible advantages might offset the increased cost: first, it would be possible to treat hay in baled form leading to much easier handling, and secondly, as the material which requires drying is heated directly instead of having air passed over it, appreciable economy in the energy required should be obtained.

Mr. C. M. Roberts: There are sound reasons for building power stations underground when conditions are suitable: the topography may be such that an underground station is more economical, and there may also be reasons for design and amenity.

For passing fish across a dam the paper mentions the Borland pass. This works satisfactorily for medium dams, but for dams with a large range of water levels it may become too complicated. The choking of salmon and smolt screens by debris in time of flood creates a major problem. This builds up a hydraulic head on screens and supporting structures, and calls for a design strong enough to cope with conditions of full blockage, or for a more economical structure with special precautionary measures to prevent overstressing. Among such measures being developed are (*a*) electrical control equipment to give warning when the safe limit of head is being approached, and (*b*) the provision in certain screen panels of supporting bolts which would fail at a pre-arranged stress and so relieve the water pressure.

The choice of type of dam depends not only on the topography of the site and availability of suitable materials, but also on the labour conditions prevailing in the particular country affected.

The use of wet-ground blast-furnace slag to save cement in concrete has been mentioned. Further economies could be effected by drying out the slurry, thus making it easy to handle and transport to sites remote from the grinding plant.

Finally, on the question of pumped storage, it might well be that certain stations in the remote Highlands, operating as run-of-river stations or on partly regulated flow, could provide night and weekend output for associated pumped-storage schemes, thus using the unregulated water instead of letting it run to waste.

Mr. J. C. Beverley: Before the war there was comparatively little hydro-electric development in this country and British

manufacturers were therefore at a great disadvantage compared with Continental competitors. Now, with the great variety of schemes which are touched on in the paper, British manufacturers have the opportunity of testing out in the field those new designs which must always be brought forward to deal with competition from oversea.

In the first station of the Snowy Mountains Hydro-Electric Development two turbines and alternators which are exact duplicates of the Sloy machines have been installed. The Snowy Mountains Authority went on from that to a second station with four sets, where the head increased from the 810 ft of the first station to over 1 000 ft, and the turbine output to 129 000 h.p. each. Likewise, in a scheme in Canada, with a head the same as that at Sloy, the output of the turbines which were designed in this country has gone up to 175 000 h.p.

Reference has also been made to breaking into the American market with hydro-electric plant. A contract for two very large 85 000 kVA low-speed alternators (85·7 r.p.m.) for a station in the United States came to this country through the development carried out in a hydro-electric station in Scotland, particularly with a static form of voltage regulator.

Reference has been made to the Sron Mor scheme in Scotland, which is a pilot pumped-storage scheme. That station is of interest, too, because it is giving experience in large induction generators, which can be used for those schemes which might be termed marginal from the financial aspect.

It will be interesting to know how far the development of such a 'utility' scheme can be pursued further in Scotland when otherwise the scheme would be uneconomic.

On the interesting point of the high-capacity high-head pumped-storage schemes referred to in the paper, it would be interesting to know how far it will be economic to develop these in stages, and thus to take advantage of the latest advances as they are made available.

Mr. A. R. Cooper: I had not intended to speak, but Mr. Roberts suggested that basic slag should not be used in the wet-ground condition and this prompts me to suggest that it should not be used at all. I suggest that, instead, Mr. Fulton should try pulverized fuel fly ash from our power stations, which is already dry, does not need grinding and has the pozzolanic property of setting with lime under water. If he has not tried it, I strongly recommend it.

Mr. D. J. Bolton (*communicated*): Section 2.7 suggests that the electricity generated by the Board might be regarded as a saving of imported coal at £6 per ton. This is marginal costing with a vengeance. At this rate any colliery in the country could claim to be working 'at the margin' and say that, but for their production, so much coal would have to be imported at a cost of £6 a ton. By the same token, our total coal output is worth about £1 300 million. Hydro-electricity is only one of a number of ways of saving coal by additional capital investment. Main-line electrification, for instance, would save about ten times as much coal as the whole of the Board's system, and would hardly require ten times the investment.

It is a pity that the only section of the paper which attempts an economic assessment should have taken its stand on the ground where the scheme is weakest. At load factors such as those mentioned, hydro-electricity is likely to prove a very expensive way of saving coal, but it may be an economical way of gaining electric power. This should prove increasingly important in an atomic age—as the paper itself recognizes—and an assessment of the cost per kilowatt would have been more valuable than the somewhat shaky claim made for the kilowatt-hours.

Mr. H. Headland (*at Manchester*): The paper is a tribute to the foresight, patient perseverence, vision and versatility of the late Sir Edward McColl and Thomas Lawrie, who were regrettably not spared to see the confirmation of their faith in the value of hydro-electric power in the rehabilitation of the Highlands. It confirms that intangible economic and social benefits follow hydro-electric development in sparsely populated areas as in the Tennessee Valley, where the main objectives have been to assist agriculture and to prevent the drift of population away from the land. It records the improvement, not the destruction, of scenery and salmon fisheries and the revival of the stone-mason's craft, and a tribute from the Council for Preservation of Rural Scotland. It shows the benefits of indirect flood control, improved road access and utilization of peat.

British and Scottish industry have profited from the Board's activities, for before the war it was relatively inexperienced in water-power plant, but it is now able to compete with a reasonable chance of success in foreign markets. These benefits cannot be assessed economically, nor do they enter into the criterion as to whether a hydro-electric scheme is justified in terms of pounds per kilowatt or pence per kilowatt-hour relative to the cost of generating the same output in a thermal station, on the basis of which the Board has to operate commercially in the face of limitations of capital expenditure, rising costs and interest rates, which have such an important bearing on water-power economics.

The civil engineering aspects of the Board's work have been described in the *Proceedings of The Institution of Civil Engineers* and elsewhere, but the power stations cover a wide range of water turbine, alternator and governor types with different outputs as well as other types of plant, and this is perhaps the place to record the need for a paper outlining mechanical and electrical developments, operating experience and troubles, although the latter have not been serious. Such a survey might well be extended to questions of availability, operating and maintenance costs, the need for standby steam- and gas-turbine plant on an essentially hydro-electric system, and co-ordination of system operation on an interconnected network where diversity of rainfall and run-off have to be considered.

Loch Sloy gives another example of Mr. Lawrie's foresight, where circumstances have brought the scheme through a full cycle from pump storage, straight hydro-generation, back to pump storage.

The Board is able to dispose of all secondary energy from its stations and pump storage has not hitherto been an attractive proposition, but with the advent of nuclear power the outlook on this type of plant and on station load factors generally has changed. Ffestiniog will have a capacity of 300 MW in four 75 MW conventional vertical-shaft units with pumps discharging about 650 cusec against a 1 000 ft head. The hydraulic conditions are similar to those at Loch Sloy, but the reference to a capacity of 2 000 MW should be an incentive to industry to develop high-head reversible turbine pumps; these have obvious technical and economic advantages, but their application is dependent on the satisfactory solution of hydraulic problems as well as electrical questions involving motor starting, transmission and system operation.

With regard to the utilization of the peat bog in Caithness, one might ask whether removal may not bring some risks or problems with it.

It may be of interest to note that, whereas the Board wishes to eliminate eels, another hydro-electric scheme places great value on them as a source of revenue. Both salmon and eels can influence the type of turbine to be installed. Although the paper passes rather casually over this topic, it is one which needs further investigation before uniformity of ideas can be reported.

Mr. W. Brittlebank (*at Manchester*): I should be interested to learn whether the Board has been able to compare the results of the new Borland type of fish pass with the pool type. I should

also like to know whether any other authorities are now considering buildings constructed in masonry, or whether this type of work will finish when the Board's construction is completed.

A figure of about 10 000 million kWh per annum is mentioned in Section 2.7 as the ultimate capacity in Scotland, not all of which is at present economic; but in years to come, as coal becomes scarcer and probably dearer, and civil engineering methods still further improve, the majority of this figure may, in fact, be worth developing. The recent White Paper on nuclear power states that 2 000–4 000 MW of hydro-electric power and pumped-storage power may be commissioned by 1975. Obviously, Loch Sloy may provide a suitable site in Scotland, but I would suggest that, wherever possible on any of the larger schemes still to be constructed, it might be most economic to combine pumped storage with the natural hydro-electric power so that the pipeline or tunnel and reservoir costs need not be debited against the pumped storage.

No mention has been made of communication and control equipment. The Board has installed a comprehensive system in which power-line carrier channels have been installed on all the main 132 kV lines. The channels have a nominal bandwidth of 4 kc/s and can be used for speech in the audio band and voice-frequency telegraphy in the super-audio band. The telegraphy equipment is of the two-tone type and incorporates channels for telemetering, telephone signalling and supervisory control and indications. In addition, the carrier system incorporates 132 kV line protection. As most of this equipment is now in service, I should like to know about the Board's operational experience with it.

Main control of the system will be from the central control room located a few miles south of the Errochty switching station. The central control arranges for the outputs of each group of stations and also co-ordinates the export of power to the South of Scotland Electricity Board. In addition, each group of stations has a group control room which co-ordinates the output in each of its stations, and has automatic indication of important reservoir levels and river flows, and controls those stations and substations which are normally unattended. I gather that the majority of the future stations will be of smaller capacity and higher load factor than those already in commission. In general, would it be more economic to run these unattended and have them controlled, if possible, from some existing group control room?

I should like to have information on the outage factors of the major equipment such as turbo-generators, transmission lines and transformers.

Mr. A. B. Washington (*at Manchester*): In other supply areas in Britain, mostly steam operated, tariffs differ for a variety of reasons, though they are progressively tending to become equalized. However, I understand that the North of Scotland Hydro-Electric Board is by statute bound to export surplus energy to other areas at the same tariffs as obtain inside their own area. Surely it is more costly to export supplies than to consume within the 'home' area, and some differential in the tariffs might therefore be expected.

Furthermore, the Board is specifically required, unlike the other areas, to collaborate in measures for the economic development and social improvement of its own area.

Mr. A. I. Jones (*at Manchester*) referred to the substantial nature of the buildings and inquired whether any consideration had been given to cheapen construction by the use of alternative cladding materials such as light sheeting.

Mr. J. Taylor (*at Newcastle upon Tyne*): I was surprised to learn that power stations constructed in stone had sometimes been found to be a little cheaper than those constructed in reinforced concrete. I would have thought that a solid masonry building would have been much more expensive, but I suppose it largely depends upon the nearness of the power station to the quarry from which the stone is obtained and how much can be saved in transport costs. I believe that on some projects the stone which has been taken from the tunnel has been used to build the power station, in which case I could understand that such a building would be cheaper than a reinforced concrete building.

Joiners are essential for erecting shuttering for reinforced concrete, and I wonder if the acute shortage of these in the more remote sites partly tends to influence the Board in favour of stone, as well as the desire to encourage a native industry and to have buildings which merge with the surrounding countryside.

I should be glad if a statement in Section 6.1, regarding the pumping of surplus water from the lower to the upper reservoir in wet weather, could be clarified. It seems to me that this statement is possibly only applicable to the particular scheme quoted.

From the general aspect one would expect that pumping is normally carried out during off-peak periods. With the example quoted, however, it is probably necessary to pump during wet weather, at off-peak-load periods, since the lower reservoir forms the headpond for the Lower Shira power station. If this station was not running, the water in the headpond might rise to such an extent, owing to the run-off from its own catchment area, that dam spilling would occur, whereas this water could be pumped back and stored in the upper reservoir and ultimately be put to good use.

The proportion of farms and crofts now supplied with electricity has risen to 45% since the Board's inception and work is in hand to raise this figure to 75 or 80% before the end of the present decade. I wonder if this development can be economically justified? Presumably those consumers who have up to the present been connected will have paid some nominal 'leading-in' charge, and I think it is reasonable to assume that the easiest and cheapest ones will have been connected first. What of the more remote homesteads? Is there in fact a demand for electricity in those parts where its installation might put the owner or tenant to considerable expense?

REPLY TO THE ABOVE DISCUSSIONS

Mr. A. A. Fulton (*in reply*): I want to thank the various speakers for their contributions. Where these contained an elaboration of points touched on in the paper I do not propose to make any further comment.

Sir Charles Westlake has explained how he was converted into becoming an advocate of supplying every possible consumer without asking for any guarantees. That was initially the Board's policy, but economic circumstances have begun to weigh more heavily, and are now making it increasingly difficult for the Board to go as far as they had at first hoped.

He is quite right in observing that some of the controversy which had previously been associated with hydro-electric activity has largely died down. This applies mainly to amenity and, to some extent also, to fishery matters. Some still remains, however, but in a new form. It comes from those who, though they have received the benefits of a supply of electricity, want to have it at less than cost or at what they describe as 'pithead prices'.

Mr. Haldane, who has been associated with the work of the Board since its inception, has explained how, over the period, views have changed and low-load-factor power is now be-

absorbed with less difficulty than many people at one time would have agreed was possible. He has always been an advocate of pumped storage and particularly the superimposition of it on ordinary hydro-electric schemes because of the assistance it gives in ensuring that ample storage is available when needed. The whole question of pumped storage and its integration with thermal power could well be the subject of a special paper, and so it is hoped that, with the experience which will be gained not only on the small pumping plant which the Board are to commission on the Shira Scheme, but also on the larger one which is being developed by the Central Electricity Authority, someone will take an early opportunity of producing one.

Mr. Peattie has drawn attention to the difference in the definition of the Hydro-Electric Board's duties and those of the Central Authority, as set out in the Acts which created them. An onus is laid on the Central Authority to maintain an efficient and economical supply of electricity, whereas, in the case of the Board, no reference to efficiency is made. In practice, however, as already mentioned, the Board's consumers are taking good care to see that they get their electricity as cheaply as possible. The Board, moreover, are creating permanent assets which are proof against the advance of inflation and will ensure for posterity electricity at minimum cost.

Lord Hurcomb has stressed the importance of considering the effects of engineering works on amenity and landscape and to the biological consequences of these works. When the International Union for the Protection of Nature holds its Assembly in Edinburgh this summer, they will be encouraged to visit the Board's works. They will thus have the opportunity of associating themselves with Lord Hurcomb's tribute to the Board's efforts to minimize the effects of their works.

Mr. Mountain asked for details of the effect of the drought which occurred in Scotland last year. In the areas of the Board's schemes, the actual run-off was only about 72% of the average. This figure would have been considerably lower but for the month of December, which contributed 17% of the 72% mentioned. Unfortunately, some last-minute difficulties arose at Invergarry, and so that set was not running before the end of the year as had been expected.

The average capital cost for connecting each new consumer in 1954 was £184, and because the remaining consumers are steadily becoming more expensive to connect, it is expected that in 1955 the average cost will have risen above £200. Rural consumers are mainly responsible for these high average costs of connection and so clearly are not paying what it costs to supply them with electricity. In the crofting counties the deficiency is about £5 10s. per annum per consumer.

In reply to Mr. Braikevitch, the head of the pumped-storage scheme referred to in the paper is within the range 750–950 ft. This and other similar pumped-storage schemes, of which there are several in Scotland, will afford manufacturers plenty of opportunity to solve the problem of producing in one unit a reversible turbine pump. That industry in this country is fully alive to pumped-storage needs is evidenced by the substantial order obtained for the Niagara pumped-storage scheme, and in the solution of the problem of relieving the pump starting torque by the ingenious method illustrated by Mr. Braikevitch.

I was most interested in Mr. Guthrie Brown's comparisons with power stations abroad and in his conclusions that the architectural results in Scotland were so much better.

Mr. Ferguson referred to the problem of recruiting and training sufficient skilled staff to operate the remote stations, and asked whether it was likely that a greater degree of remote control would be necessary. It was originally hoped that it would be possible to get sufficient staff to man all the Board's stations and to some extent reverse the depopulation of the Highlands. Unfortunately, such high hopes have not been realized, because, for one reason or another, it has been more difficult to get people to live in these remote places than had been expected. This has not always been due to the man himself, but sometimes because he has been unable to persuade his wife to live where there are no shops or other town facilities.

The remote-control solution is not necessarily the answer, because it is well known that such equipment requires attention from specialists. It could be even more difficult to persuade people in that category to live in our rural areas.

So far, the Board has not given serious consideration to d.c. transmission. The opportunities of using it are not so favourable as in the Sweden–Gottland scheme. To be worth while, the distance to be travelled and the size of the load are important. The Board's outlying islands were not sufficiently attractive in these respects.

Hay drying by high-frequency methods has been considered, but has not been pursued because the main emphasis on providing facilities for hay drying had been to find a method which involved the lowest capital expenditure. High-frequency drying did not come into this category.

Mr. Roberts is in favour of underground power stations where conditions are suitable. Experience has shown that there is usually very little difference in cost. The advantage has usually been decided in terms of economy in cement or steel and not in money.

He was inclined to doubt the suitability of a Borland pass for dams where there was a large range of water levels. Actually, no matter what type of fish pass is used for reservoirs with large variations of water level, the problems are considerable, and I would be inclined to think these are no worse to solve with the Borland pass than with any other.

The problem of fish, and particularly smolt screens, certainly deserves further study. Serious problems can arise if such screens should collapse as a result of choking. The use of revolving screens in hydro-electric works does not seem to have been explored as energetically as it might; a solution may lie along these lines, notwithstanding the physical dimensions involved.

One reason why there has been no extension of the use of wet-ground slag has been the cost of drying. So far, no one seems to have produced a method of doing this sufficiently cheaply to make the material competitive for use on sites remote from where the slag is ground.

While run-of-river stations are a suitable source of power for pumped storage, there are relatively few of these in the Board's Area, and experience shows that their capacity is generally only about equal to the Board's night load, so that any surplus left over for pumped storage is too small to be worth while.

Mr. Beverley asked how far it will be economic to develop pumped-storage schemes in stages. So far as the plant is concerned, there is no real problem, but it would be expensive to proceed with civil works for a complete development, as this would mean that the first stage would be saddled with more than its share of the capital cost. The idea might therefore prove difficult to justify in practice.

Mr. Cooper recommends the use of pulverized-fuel fly ash rather than wet-ground blast-furnace slag. The Board has actually used both, and there is quite a difference in the merits of the two materials. Fly ash is really less useful as a saver of cement. It is only possible to replace 20–25%, as against 70% or more with slag. Moreover, the two materials have different properties. Fly ash is not strictly an equivalent material to cement, for its action depends on its combination with the lime set free when the concrete sets.

Mr. Bolton criticizes the argument about coal saving by hydro-

electric investment. No claim was made in the paper that hydro-electricity was developed primarily to save coal. It does, however, represent an added dividend. If any expenditure, whether it be on miners' wages, investment on railway electrification, or in hydro-electricity, should reduce the need for imported coal, that surely is in the country's interest. There is no need to look for marginal advantages for hydro-electricity. In Scotland, at any rate, no scheme has been proceeded with unless the power produced is to cost less than the current cost of production by equivalent thermal power.

I support Mr. Headland in his suggestion that, as most of the papers and articles which have appeared describing the work of the Board have dealt mainly with the civil-engineering aspects, there should now be one dealing with mechanical and electrical operating experience.

Mr. Brittlebank asked whether the Board has been able to compare the results of the new Borland type of fish pass with those of the 'pool' type. Although experience is, as yet, somewhat limited, there has, so far, been no noticeable difference; in fact, it is expected that the Borland pass may prove more helpful for descending fish than the orthodox 'pool' type because of the possibilities of increasing the discharge through the Borland pass, and thus the draw, in a way which is not possible with the 'pool' pass.

So far, industry generally has not followed the Board in the use of stone, but it must be remembered that, in the Highland area, with its limited industrial development, there are few opportunities for this. On the other hand, as the result of the Board's example, some local authorities are building more of their houses in stone.

I do not agree with Mr. Brittlebank's suggestion that where pumped storage is associated with natural hydro-electric power, the tunnel and reservoir costs should not be debited against pumped storage. I do not see the justification for that argument, and, in any case, for a really big pumped-storage scheme, the cost of the upper reservoir is, in general, a relatively small percentage of the total cost.

Smaller stations, especially those with a single machine, do not justify a rota of shift attendants, but some local staff are needed to keep screens clean, do cleaning, greasing and daily maintenance in the stations, show visitors round, etc. The plant in these stations is made sufficiently automatic and self-protecting to allow it to run unattended. Starting and stopping is carried out by attendants, and an alarm circuit from the plant is laid on to the attendants' nearby houses.

The availability of the main turbo-alternators has been very good, and few major difficulties have developed which involved shutting a machine down immediately. Such failures as have occurred have mostly been due to secondary matters, such as control-circuit troubles, cable-box breakdowns, etc. There has been no breakdown on 132 kV transformers, but there have been difficulties with ice loading on 132 kV lines. These have occurred at widely separated places at different times, which makes it difficult to take precautions. Under icing conditions, vertical formation of conductors is a weakness. Conductors are not always uniformly weighted with ice or snow, nor do they shed it simultaneously. As a result, there have been a number of faults caused by conductors clashing.

The basis of the Board's charges for export to other areas is not quite as stated by Mr. Washington. Energy which the Board may have for export is sold, not at the tariffs which apply to ordinary consumers in its own Area, but either at a statutory price defined in the 1943 Act or at a price agreed with the receiving authority. The agreed price basis is actually what applies and it has a kilowatt and a kilowatt-hour charge which make it comparable with the C.E.A.'s bulk-supply tariff.

Mr. Jones has asked whether consideration has been given to cheapening the cost of the Board's main buildings. Such considerations are always kept in mind, but naturally, under the extreme weather conditions usually experienced in the Highlands of Scotland, there is an advantage in having reasonably substantial structures. In any case, the cost of the cladding of a building is a very small percentage of the total cost of a hydro-electric scheme and economy in this direction might in the long run, owing to extra maintenance, be more expensive. The long life of hydro-electric schemes also favours the use of a durable cladding.

Mr. Taylor wonders why power stations constructed in stone are sometimes cheaper than those of reinforced concrete. The reason is that in the remoter parts of the Highlands and in the Islands nearly all building material, including cement and bricks, has to be imported. In Orkney, on the other hand, where a large Diesel station had to be built, good building stone and masons were available locally, and so it was possible to construct there a masonry building cheaper than in concrete or in brick. In other cases, too, it has been possible to use material excavated from tunnels. One of the recently commissioned stations in Perthshire was built of this material, and as the stone is of a pinkish colour, it looks most attractive. Where masonry walls are solid, it has been possible to dispense with any form of inside finish; in other words, the Board has copied the old ecclesiastical buildings and used a stone finish both inside and outside.

The statement in Section 6.1 regarding the pumping of surplus water from the lower to the upper reservoir applies only, of course, to the Shira scheme. It was decided to do this partly as an experiment and also because of the relatively small capacity of the lower reservoir into which a substantial amount of water was gathered from catchments at lower elevations.

The high percentage of connection of farms and crofts has only been done at a sacrifice by the Board, and naturally the easiest and cheapest ones have been done first. The problem of the more remote ones still remains, and at present it looks as if some substantial contributions will be necessary from the consumers concerned if they are to get the advantage of an electricity supply.

Many of the speakers have paid tribute to the work done by Mr. Lawrie. He was recognized as one of the great pioneers of hydro-electricity in Scotland and the schemes with which he has been associated and the extent to which electricity has been made available throughout the Highlands will be a lasting memorial to him.

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ELECTRIC TRACTION

A Review of Progress

By J. W. GRIEVE, B.Sc., Member.

Six years ago the Convention on Electric Railway Traction[1] reviewed electric traction with special reference to British Railway electrification at home and oversea, and the last ordinary progress review on this subject covered the period, January, 1933, to December, 1936.*

The present review does not include Diesel-electric traction, which now merits independent treatment, but generally records trends and developments since 1936 with some reference to progress in most of the principal countries of the world.

There is no doubt that the most important feature of the period has been the development of electric traction using single-phase alternating current at standard frequency directly on the contact system, and the progress made in the application of this system has been very largely due to the imagination and drive of French engineers.

(1) POWER SUPPLY AND TRACTION SYSTEM

At the present time the main traction systems for extensive railway application are:

Direct current ..	1 500–3 000 volts.
Alternating current	Low frequency at 11–16 kV.
	Standard frequency at about 25 kV.

The balance between direct current and low-frequency alternating current has been fairly evenly maintained, but the growing possibilities of reducing the heavy capital outlay, the chief obstacle to railway electrification, offered by the standard-frequency a.c. system have demanded the closest investigation. The saving compared with direct current is almost all in the cost of fixed installations, i.e. the power supply and the contact system. Their cost includes a large element dependent on the number of miles of track to be electrified. The lower this cost, the lower is the traffic density necessary to provide working economies by electrification. It is hoped that the standard-frequency system will widen the scope of electrification.

The growth of industrial loads and the development of electricity supply systems have removed the problem of supply from the railway to the public supply authority. The effect of traction loads on industrial power networks was discussed at the World Power Conference in Delhi in 1951,[3] where the benefit to railways and other consumers by the joint use of one generating and distributing system were clearly stated.

There is now no difficulty in using public supply at standard frequency for d.c. systems. The rectifier solved this problem, although it has not yet been developed so as to replace the less efficient motor-generator set for single-phase low-frequency a.c. traction systems.† The motor-generator, however, can be compensated to give voltage regulation on the power supply side, a practice widely adopted in Sweden. A traction system using alternating current at standard frequency is obviously the simplest from the viewpoint of power supply.

In the d.c. systems, it is common practice for a railway to take supplies at a limited number of places and to install its own distribution system. It is sometimes even possible for individual supplies to be taken at each substation from a medium-voltage public-supply network. This has been done to a large extent in Holland, and for the present extension of the Liverpool Street–Shenfield electrification to Chelmsford and Southend (Victoria), the Central Electricity Authority has given an independent supply at 33 kV to each of the four new traction substations.

The a.c. system permits increased spacing of feeder points, but the 16⅔ and 25 c/s systems still demand a special low-frequency supply. With a standard-frequency single-phase supply there is increased impedance as compared with the usual low-frequency system, and it is therefore advisable to select as high a line voltage as possible. This led to the raising of the voltage of the single-phase 50 c/s French experimental Annecy line from 20 kV to 25 kV. The Valenciennes–Thionville line at 25 kV has six substations and 7 miles of h.v. feeder, whereas 23 substations each more expensive than with alternating current and some 211 miles of h.v. feeder would have been required for 1 500-volt d.c. electrification.[10]

It must be recognized, however, that a high-voltage contact line brings its own very serious problems of electrical clearance through tunnels, under bridges and other structures. For 1 500-volt d.c. systems the minimum clearance required by the Ministry of Transport is 4 in, whereas the recommended clearance for 25 kV a.c. is likely to be 11 in. The expenditure under this heading could be very high in large cities.

One of the problems of direct single-phase standard-frequency traction loads is the unbalancing effect on the 3-phase system. This is largely related to the proportion of the railway load to that of the power supply system at the point of delivery and the characteristics of the system.[9] In original installations two methods of connection have been used in the distribution of the single-phase traction load between the three phases of the public supply. The first method was by means of Scott-connected transformers and was adopted for the Annecy electrification; the other method was to divide the contact line into sections, each connected to a different phase, and this was done on the Jadotville–Tenke electrification in the Belgian Congo. The Scott connection, which will partially overcome single-phase unbalancing, was adopted on the Hollenthal line, but was discontinued as it was not found to have a material advantage over a single-phase connection.[4]

The supplies for the Valenciennes–Thionville section in Northern France were taken at 63 kV or 45 kV, with a short-circuit capacity of 300 MVA or less, from Électricité de France at points about 40 miles apart. Some supplies were given by two single-phase transformers as at Valenciennes, or by two Scott-connected groups as at Mohon. The transformers carried 5 000–10 000 kVA in each substation.[13]

The results of the Valenciennes–Thionville electrification, begun in August, 1954, show that it was possible to make considerable single-phase power demands within the permissible amount of out-of-balance load. This is supported in a minor degree by the experience of the Lancaster–Morecambe–Heysham single-phase supply taken directly from the public system. The ever-increasing development of public supply systems should facilitate

* *Journal I.E.E.*, 1937, **80**, p. 181.
† There was an experimental installation at Basle.

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the acceptance of unbalanced loads resulting from single-phase supplies at standard frequency taken from 3-phase networks, and it is foreseeable that in the future the traction substation will be readily absorbed in the national Grid.

(2) SUBSTATIONS

There is little radically new to report regarding d.c. substations. In Great Britain where e.h.v. cables are necessary, the present practice tends towards the use of oil-filled 33 kV cable, continuously supported and protected in concrete troughing. Buildings are becoming smaller with more compact design of plant to which the development of the d.c. high-speed track-type circuit-breaker has contributed. There has been a change from the outdoor h.v. switchgear used in the country extensions of the Southern Region and the Shenfield electrification and in many Continental installations. Unit-type indoor metalclad h.v. switchgear is now preferred on the grounds of safety and easier maintenance.

Rectifier design has become more compact. The pumpless steel or glass-bulb units are standard in Great Britain and many of the Dominions, and have a very good record of reliability.

Research into rectifiers has led some to use single-anode units in substations. The French National Railways[11] installed in a substation on the Paris West suburban lines two groups each of 3 250 kW, 650 volts. The rectifiers are of the pumped type with six steel tanks per equipment. On the 1 500-volt Lyons–Culoz section, electrified in 1953, four substations were equipped with 2 000 kW sets in each. Three of these have vacuum-pumped excitrons cooled by forced air, and the fourth, at Montluel, has water-cooled pumpless ignitrons. The units are easily replaceable, and the reduction in size and weight, with attention to other details, has resulted in a simplification of buildings and layout, giving a total saving of about 40% in the cost of comparable substations on the Paris–Lyons line.

Where regenerative braking is required, grid-controlled rectifiers, as used on the South African Railways, could be installed, though some simpler apparatus is desirable. On the Manchester–Sheffield electrification, loading resistances with electronic control have been provided. Another interesting development is the incorporation of electronic arc suppression, which, when a fault occurs, causes a strong negative bias to be applied to all control grids, so preventing any further output of current from the rectifier. This device has been reported to be of greater use with rectifiers giving 3 000 volts, and possibly 1 500 volts, than with those supplying lower voltages.

During the past decade it has been the practice in this country to install remote-control supervisory apparatus of the centralized type. Control on the d.c. impulse system is effected from master panels which do not present a permanent record of the conditions obtaining on the system and necessitate the provision of a mimic diagram dressed by the operator. In the new Southern Region change-of-frequency scheme, a return has been made to the system in which each item of equipment has its individual control switch in its correct position on the mimic diagram. The diagram in the Raynes Park control centre covers 28 substations with associated track sectioning cabins involving the control of 527 circuit-breakers. In the design of this equipment special attention has been given to the speed of operation. As an example, the total time from the receipt of a trip alarm to the reclosed indication is 8·3–13 sec, and track feeder breakers at substations can be operated in groups as well as individually. Separate control and indication cable cores are used to avoid delay. It is possible for two 'perfect' operators to restore power on the whole system, after every switch has opened, in approximately 5 min.

An interesting development in substation control is the use of voice frequency over 97 miles of the Gippsland electrification of the Victorian Railways. From the control centre at Warragul, control impulses and return indications are sent simultaneously over the same pair of wires, for the control and indication of 16 substations and 12 track sectioning cabins. Voice frequency, selected from the 660–2 460 c/s band, is also used for the control of substations and track sectioning switches from the central control station at Charleville on the recent 50 c/s electrification in Northern France.

(3) OVERHEAD TRACK EQUIPMENT

Developments during the period under review have in the main resulted from the endeavour to reduce the costs of construction, installation and maintenance. A recent paper before The Institution[6] sets out British practice for 1 500-volt d.c. systems and suggests modifications for economies such as longer spans between structures on open lines, smaller and less costly foundations, reduced wind loading, increased stress in steel, reduced minimum thickness of steel, etc. Many of these recommendations have been adopted in the design and installation of overhead equipment for the Shenfield electrification extensions to Chelmsford and Southend, now in progress. It has been considered possible, for instance, to reduce the equivalent copper cross-section from 0·75 to 0·6 in^2, and to increase open line spans from 210 to 240 ft, compared with previous practice. A power-driven auger has been used for foundation excavations on recent French electrifications and also in the Belgian Congo. A similar method was adopted for the Shenfield extensions, where the auger, mounted on a wagon, bored the foundation holes of a diameter and at a depth depending on the nature of the ground. This was followed by the steelwork erecting unit, which lifted the masts and placed them in the holes, where they were held in the correct position by a frame. A third concrete-unit train then filled the excavations.

Reinforced concrete for structures had been used before the war, but the need to save steel turned attention again to the possibilities of concrete. In the rehabilitation of the war-damaged Netherlands Railways, many miles of track were equipped with hollow Arkel masts of vibrated concrete carrying arched cross-beams of reinforced concrete with straight tie rods. Meanwhile, the French National Railways had developed the use of prestressed concrete on the Weinberg system, for the electrification of the Paris–Lyons lines.[17] Similar structures, but with important modifications in production technique, were subsequently used in Holland. Recently, on account of timber shortages, concrete structures have largely replaced the wood poles formerly used in Japan. Their economic advantage, compared with steel structures, lies in the fact that they do not require painting, rather than in first cost. But careful handling is required and there is a possible risk of collapse under impact. Their greater cross-section does not improve signal sighting. Prestressed concrete structures were considered unlikely to be economical for junction work, but it is possible that single-track cantilever masts will be economical if mass produced. A number of prestressed structures, portal and single masts, are being installed on the Shenfield electrification extensions for trial purposes.

Steelwork protection, especially in urban districts and where mixed steam and electric services are run, is a problem. Present practice favours the galvanizing rather than the flame-cleaning of structures, before assembly, as the best initial treatment.

Bronze catenary is largely used on the Continent, but cadmium-copper, with a considerably greater conductivity than a 60% bronze and of very nearly the same tensile strength, is preferred in Great Britain and many of the Dominions. Cadmium-copper contact wire is superseding hard-drawn copper, especially on main lines. The use of two contact wires is favoured by some

administrations as giving better current collection. Methods of suspension of the contact wire vary considerably from line to line. Inclined catenary construction for curved track is common in the United States, and though the railways using it report no difficulty in keeping it in adjustment, the use of the compound catenary system for new construction is favoured.

(4) MULTIPLE UNITS

The value of the multiple unit has long been recognized in suburban electrification, and it has become increasingly used for inter-urban services and high-speed operation between large cities.

Electrically there is little to report beyond higher standards in lighting and heating and minor improvements in the design of control equipment. Greater output from machines of a given size and weight is being constantly sought, but the limiting factor has been the ability of the insulation to withstand high temperatures. New insulating materials based on silicones present ways of increasing the previous temperature rise. In view of improved traction motor design and technique it is no longer considered necessary in this country to draw air for self-ventilated traction motors through bellows, connections and ducts in the coach bodies. Motor-driven camshafts are favoured in present Continental practice. With the usual d.c. series-parallel control, economical speeds are limited, even with a number of weak-field notches in parallel. On motor coaches for the French south-eastern region, weak-field notches have been provided in series to give an economical higher running speed over the fairly long runs in suburban areas before reaching the open country, where maximum speeds can be attained.

In a.c. traction, interest centres on motor coaches for use on standard-frequency lines. The a.c. series commutator motor seems to provide the simplest approach, and three motor-coach trains of this type are run on the Annecy line as against one with ignitron equipment. But the 50 c/s traction motor presents a number of serious problems to the designer, the most difficult of which is that of satisfactory commutation. Some improvement has been effected by the use of divided brushes, which provide transverse resistance to the short-circuit current. Another method is to use resistance connections between the armature winding and the commutator.

The first large-scale use of a.c. series commutator motors at 50 c/s in suburban service was that on the Turkish State Railways, put into operation towards the end of 1955. Meanwhile, experience was being accumulated on the use of rectifiers and ignitrons on motor coaches. The New York, New Haven and Hartford Railroad has put (1954–55) 100 ignitron-equipped motor coaches into service which operate from an 11 kV single-phase 25 c/s supply. In the experimental tests of single-phase 50 c/s traction in this country, attention has been directed to the use of d.c. motors, and while the first trials were with multi-anode rectifiers, tests are now being carried out with air-cooled ignitrons and also a germanium rectifier. British manufacturers are taking the lead in the development of semi-conductors for rectification on motor coaches which promise compact equipment of low weight with greater efficiency. But the application of rectifiers to rolling stock brings its own problems.[7]

The increasing cost of fuel emphasizes the importance of weight reduction consistent with strength and reliability, and London Transport have put into service prototype trains with aluminium-alloy bodies, and also bogies incorporating a system of rubber in shear in place of steel springs. In Paris, pneumatic tyred 4-coach sets have been built for the Châtelet–Mairie-des-Lilas Metro line, following experience gained after two years' trial.

Motor-coach stock for high-speed services calls for attention to bogie design to ensure good riding. Although the merits of spring-borne or axle-hung motors have been the subject of close investigation, there is little conclusive evidence in favour of one or the other with regard to effect on the track. Many forms of flexible transmission have been tried and abandoned. The original Brussels–Antwerp motor coaches were fitted with Sécheron drive, but later types have simple axle-hung motors, even those which operate on services with a maximum speed of 87 m.p.h. Whereas the experimental motor coaches on the 50 c/s Annecy line were fitted with spring-borne motors with forced ventilation, those for the Turkish 50 c/s electrification have simple self-ventilated axle-hung motors.

(5) ELECTRIC LOCOMOTIVES

The modern high-speed electric locomotive with all axles motored stems from the Swiss designs for the Berne–Lotschberg–Simplon and Swiss Federal Railways, introduced in 1946. The 2 400 h.p. 56-ton B_0–B_0 Swiss Federal and the 4 000 h.p. 80-ton B_0–B_0 for the Lotschberg line began a new chapter in electric locomotive development and have had a marked influence on Continental design.

Inability to export during the war gave the Swiss engineers the opportunity of concentrating on design, and they tackled the question of providing higher speeds with safety, comfort and economy. To meet air and road competition they saw that railway speeds must be raised as high as possible. The result of their efforts is mainly observable in weight reduction and improved bogie design. In this way, higher accelerations are possible with higher speeds on gradients and curves, with less damage to track.

Before 1946, nearly all Swiss locomotives, whether passenger or freight, had their driving axles on the main frame with guiding axles at each end, either in the form of a pony truck or two-axled bogie. In early locomotives the drive was generally from one or two large motors via a jackshaft and connecting rods or Scotch yoke to the coupled driving wheels. The maintenance of this arrangement was difficult, and the locomotives ran badly at high speeds. Various types of individual axle drives were developed.

The Lotschberg locomotives were among the first to be fitted with the flexible disc drive. In this method the gear and pinion are mounted rigidly on the axle and the motor drives the pinion through two flexible spring-steel disc couplings, with the driving shaft running through the hollowed motor shaft. This drive is used in some of the latest Swiss-built locomotives for the French Railways, and may be compared with French-built locomotives with fully spring-borne motors whose pinions, via an intermediate gear, drive each axle through a flexible transmission system in the form of a short Cardan shaft enclosing the driving axle and universally jointed at the one end to the gearwheel and at the other to the driving wheel. (This arrangement allows the motor size to be increased as necessary without limiting the overall size and gear ratio.) The latest Belgian locomotive, however, the 82-ton B_0–B_0, type 122, introduced in 1954, illustrates the trend, noticed in Belgian multiple-unit stock, away from the flexible-drive to the simple axle-hung motor. On all Belgian locomotives, weight transfer effects of motor torque reaction and drawbar reaction can be compensated either by electrically or pneumatically operated mechanisms.

Swedish individual axle-driven locomotives utilize a quill transmission with rubber coupling elements similar to that used on the Pennsylvania Railroad. But in the transmission fitted to the new high-speed locomotives the motor is coupled to a separate gear via a torsion shaft, connected at one end to the gear wheel on the axle by a Layrub coupling, and at the other end to the rear of the motor through an inverted gear coupling.[12]

There has been a marked trend away from the complex

problems of articulated connections between bogies, with a resultant saving in weight and greater freedom in the design and control of bogies.

In France, new post-war designs began with two types developed for the first section in 1950 of the Paris–Lyons electrification. The 4 400 h.p. 2–D_0–2 144-ton locomotive for fast passenger and freight work is an improved version of similar locomotives working on the former Paris–Orleans–Midi system. The traction motors are mounted rigidly on the main frame with flexible transmissions of the Buchli type to allow vertical and lateral movement of the axle relative to the frame. The locomotives can haul 880 tons on the level at 86 m.p.h. and 1 000 tons up a gradient of 1 in 200 at 61 m.p.h. A considerable amount of field weakening is made possible by the use of compensated motors, the minimum excitation being 29·4%, and there are 24 economical running speeds. Vernier control is provided for starting heavy trains on greasy rail.

The other type, a mixed-traffic 2 500 h.p. (continuous rating) B_0–B_0 80-ton locomotive, has axle-hung motors with single-reduction resilient gears. With a maximum speed of 65 m.p.h., it can haul a 1 050-ton train up a gradient of 1 in 125 at 35 m.p.h.

While the 2–D_0–2 type was under construction, a C_0–C_0 design of similar power with a total adhesion weight of 106 tons, 14 tons greater than that of the 2–D_0–2, was tried out so successfully that the order for the original 2–D_0–2 class was reduced from 95 to 35. These locomotives form the 7100 class and have a remarkable mileage and speed record. The majority are fitted with compensated motors and have a minimum field excitation of 27%. They have a balancing speed of 99 m.p.h. with a 700-ton train on the level.

The success of the Swiss 4-axle high-speed locomotives, which are similar in power and performance to the 7100 class but 26 tons less in weight, led to a French experiment with two Swiss and two French prototypes, the 9000 class. The Swiss designs incorporate well-tried bogies and suspension with flexible-disc drive for the motors. The French locomotives have a bogie pivoting system using lateral and longitudinal linkages with silentbloc mountings providing weight transfer, which is achieved in the Swiss locomotives by inverting the normal pivoting arrangement. The tractive forces are transmitted from bogies to body by coupling bars attached to the bogie frame approximately in the plane of the axles. Both types of locomotive have electrically operated camshaft control and incorporate forced ventilation of resistors. The traction motors are fully spring-borne, and each axle is driven by transmission gear in the form of a Cardan shaft with universal coupling.

For locomotive work, hand control of notching is practically essential at starting to cover all conditions of rail and weight of train, but it is claimed that automatic acceleration is convenient, especially in restoring power after an interruption. Probably the first installation of automatic control of notching was that of the $C_0 + C_0$ 3 000 h.p. freight locomotive developed for the Limoges–Montauban section of the French National Railways in 1950. Multi-notch camshaft control with automatic acceleration was also installed in the $B_0 + B_0$ 2 800 h.p. mixed-traffic locomotives for the Belgian State Railways having a maximum speed of 80 m.p.h. The automatic control system is rapid and permits the selection of alternative values of accelerating current. Manual control is fitted in all cases.

British locomotive practice has been restricted largely to the production of d.c. locomotives for South Africa, Spain, India, South America, Australia, etc., and in this country for the Manchester–Sheffield electrification. A typical example is the C_0–C_0 3 600 h.p. 1 500-volt d.c. locomotive for freight and passenger work over long grades of 1 in 40 on the Indian Central Railway.

The basis of Swedish locomotive design[12] has been the necessity of conforming to a maximum axle load of 17 tons and making as much weight as possible available for adhesion. For many years, rigid-frame side-rod-jackshaft-drive locomotives were universal, and up to the time of the Second World War there was virtually only one type of locomotive, a 1C1 type, increasing from 1 660 h.p. in 1925 to 2 500 h.p. in 1952 with the same motor dimensions. More locomotives of this type were manufactured than of any other single type in the world.

For the operation of very heavy iron-ore trains, 1D + D1 5 000 h.p. locomotives were introduced in 1953. With a maximum tractive effort of 52 tons, they were capable of hauling 3 500-ton trains up grades of 1 in 100. The maximum speed is 47 m.p.h., and the locomotives are among the most powerful in Europe.

The demand for higher speeds in Sweden has led to the development of higher locomotive ratings. Locomotives with the lower axle load of 15 tons are allowed to operate at 6–9 m.p.h. higher speeds than those with an axle load of 17 tons. Two locomotive types have been produced, a universal 1C1 2 500 h.p. 75-ton side-rod locomotive with adjustable axle loads of either 5×15 or $3 \times 17 + 2 \times 12$ tons (by moving the pivot bolt of the balance, a larger or smaller weight is transferred to the pony axles) and with two gear ratios to give a maximum of 62 or 84 m.p.h. The other type Ra, put into trial operation in 1955, is a 62-ton B_0–B_0 of 3 300 h.p. with a maximum speed of 93 m.p.h.

(5.1) Single-Phase Standard-Frequency Locomotives

Locomotives used on standard-frequency supplies can be divided into two groups depending on whether they use a.c. or d.c. traction motors. The types so far employed on existing installations have been so varied that it is considered advisable to refer briefly to their historical development.

The first trials of the Kando phase convertor were made by the Hungarian State Railways as long ago as 1918 on the 16 kV single-phase 50 c/s system. In 1950–1952, four 3 200 h.p. 89-ton locomotives with an unusual B_0–C_0 wheel arrangement were put into operation. In these locomotives a frequency changer was added to the phase convertor to facilitate change of speed. Although the system had advantages in the simple induction motor, high power factor, good adhesion and automatic regenerative braking, the high cost and complication of these locomotives had told generally against the adoption of this system elsewhere. But the 3-phase induction motor was attractive enough to be embodied in locomotives ordered for the Valenciennes–Thionville line referred to later.

In the Hollenthal trials (1936), two water-cooled-rectifier locomotives, one with a.c. series commutator motors and one with a phase convertor, were put on trial. Maintenance of the rectifiers and the auxiliary drives of the phase-convertor locomotive was heavy; the greatest mileage was run by the locomotive with series commutator motors, where the chief complaint was that of excessive brush wear.[4] In 1946 a fifth locomotive equipped with four double-armature series commutator motors was ordered.

Trials on the Annecy line began in 1950 with locomotives of varying design. The possibility of working into stations already electrified on the 1 500-volt d.c. systems was envisaged, and two of the original three locomotives were dual equipped, but operating at reduced power on 1 500 volts d.c. Early in 1955 a fourth locomotive was introduced—the BBB. 20003—with full power on a.c. or d.c., having a 3 800 h.p. single-phase induction motor driving three d.c. generators each of which supplies two axle-hung motors in each of three bogies.

General operating experience on the Annecy line confirmed the decision to use the same system on the industrial lines in

North-Eastern France, the first section of which to be equipped was from Valenciennes to Thionville. It was decided to use four types of locomotives, and as standardization of components had become increasingly recognized as an effective way of reducing costs, considerable attention was given to this in the design of these four types, so that spare parts were kept to a minimum. Not only was the electrical apparatus common to all types, but much of the bogie design was derived from existing and well-tried 1 500-volt d.c. counterparts. A feature of all these locomotives is the single cab, simplifying and reducing the equipment required and permitting a degree of manual control of apparatus within reach.

Freight traffic predominates on the Valenciennes–Thionville line, so that the majority of locomotives (85 out of 105) ordered to replace 304 steam locomotives were of the C_0–C_0 type. The remaining 20 B_0–B_0 locomotives were for hauling passenger and light freight trains.[10] Many of these had been in service since August, 1954.

The a.c. locomotive has an inherent advantage in starting loads requiring tractive efforts near the limit of adhesion, due to the fact that its traction motors are in parallel at all times, as compared with the 1 500-volt d.c. locomotive, whose motors are normally paired in series with resultant upset under wheel slip. On the Valenciennes–Thionville 50 c/s electrification, the French Railways, from operating experience, assess this advantage directly in terms of train loads which can be started and hauled. The a.c. locomotive was booked to haul train loads over 40% greater than its 1 500-volt d.c. counterpart of equal weight and with bogies of similar design. The 85-ton ignitron locomotives initially specified to haul 750 tonnes on up-gradients of 1 in 100 were scheduled to haul 1 400 tonnes, three months after being put into service in July, 1954. This figure has been increased since July, 1955, to 1 600 tonnes for the second series of the 12000 class locomotives on which the gear ratio has been changed from 73 : 19 to 73 : 17 (see Reference 18).

It is clear that the high capital cost of locomotives necessitates intensive use, and that the mixed-traffic type capable of high speed and high tractive effort is most desirable. The bogie-type locomotive is almost the only type under consideration to-day, but there are still many problems in the design of bogies and in the suspension and drive of traction motors.

It is difficult to foresee which of the many types of standard-frequency locomotive will ultimately prove the most satisfactory, and it may well turn out that different types for different services will give the best overall results. There has been very rapid progress in the development and application of rectifiers to traction, and many improvements have also taken place in the design of the low-frequency a.c. series commutator motor in recent years. The satisfactory development of such a motor for work on standard frequency, which would be reliable and of low maintenance cost, would bring a fundamental change in a.c. traction.[5]

(6) SPEEDS

Practically all the world's highest speed runs from 1940 to 1952 were made by Diesel-electric trains, but the three years to 1955 have seen remarkable timings by straight electric locomotives. In 1939 an experimental 3-car set of the Italian State Railways ran from Florence to Milan at an average speed of 102 m.p.h. for the 195·8 miles, the maximum speed being 126 m.p.h. To-day the fastest Italian runs are made by the 7-car luxury multiple-unit sets with a maximum speed of 98 m.p.h. operating between Milan and Naples, 524 miles. Electric locomotive performance in Switzerland, where severe curvature and gradients are commonplace, has also been very high. The Re 4/4 type B_0–B_0 locomotives weighing 57·5 tons sustain speeds of 75 m.p.h. up gradients of 1 in 100 with 300-ton trains.

But the acceleration which followed the electrification in 1952 of the Paris–Lyons main line of the French National Railways has been remarkable. The Mistral express, with its 4 h 10 min timing over the 317·4 miles is the fastest train in the world over a distance exceeding 300 miles. In winter, 28 trains each day are timed to average 60–70 m.p.h. with a maximum load of 789 tons on most of the trains. The longest regular non-stop train in the world (except for the London–Edinburgh run of the Elizabethan in summer) from Paris to Bordeaux, 359·7 miles in 4 h 59 min (72·2 m.p.h.), is electrically hauled.

This daily high-speed running is at present restricted to a maximum of 87 m.p.h., and the French National Railways are carrying out many trials to determine, among other investigations, the stability of locomotives and rolling stock, to measure the forces on the track at the highest speeds, and to study the behaviour of pantographs and overhead equipment. Thus in February, 1954, the world speed record of 151 m.p.h. was set up on a test run between Dijon and Beaune. The high-speed experiments at Morcenx culminated in March, 1955, in the phenomenal speed of 205·6 m.p.h. attained over 21 miles on the former Midi main line between Bordeaux and Hendaye by a 4 400 h.p. C_0–C_0 106-ton locomotive. This performance was equalled on the following day by a B_0–B_0 locomotive of similar horse-power weighing only 79 tons. At top speed these locomotives were developing 12 000 h.p.—an indication of the effect of wind resistance.

(7) REVIEW OF ELECTRIFICATION IN THE PRINCIPAL COUNTRIES OF THE WORLD

(7.1) Europe

(7.1.1) Great Britain.

Soon after the nationalization of railways in 1948, the then Railway Executive and London Transport Executive set up a Committee under the chairmanship of Mr. C. M. Cock to consider the future development of electrification of British Railways. The Committee's report,[2] published in 1950, endorsed the main conclusions of the Pringle Report which had in 1927 recommended the 1 500-volt d.c. overhead-conductor or the 750-volt d.c. third-rail systems as the future standards. The 1950 report proposed that, apart from an area allocated for the development of the Southern Railway third-rail system and the fourth-rail extension of the London Transport lines, 1 500-volt d.c. should be the standard system. The Committee did not rule out the possibility of 3 000 volts d.c. or single-phase a.c. at 50 c/s.

Since the war, two major 1 500-volt d.c. electrification schemes have been completed. The Liverpool Street–Shenfield suburban electrification was inaugurated in 1949, and the first stage of the Manchester–Sheffield–Wath was electrified in 1951, the final stage being completed in January, 1955.[14] Equipment in power stations and substations of the Southern Region's earlier electrified lines had reached the end of its economic life, and in 1950 the frequency conversion scheme from 25 c/s to 50 c/s was begun. The scheme provided for 300 feeder-miles of 33 kV oil-filled cable, 71 substations and 70 track-paralleling huts remotely controlled from three control stations at Raynes Park, Lewisham and Selhurst. The work was scheduled for completion in 1957.

The growing interest in standard-frequency electric traction was marked by the conversion of the Lancaster, Morecambe and Heysham lines of the London Midland Region to the 50 c/s system in 1953. The lines had been equipped for 6·6 kV 25 c/s single-phase traction by the Midland Railway in 1909 and the original plant was overdue for renewal. The 6·6 kV line voltage was retained and three 3-car rectifier trains were put into service.

Work is progressing on the 31 route-mile extension of the

Shenfield electrification to Chelmsford and Southend (Victoria), and is scheduled for completion in January, 1957.

In January, 1955, the British Transport Commission submitted their plan to the Minister of Transport for the modernization of British Railways[16]. Steam power was to be replaced by electric or Diesel traction. The Eastern and North Eastern Region main lines from King's Cross to Doncaster, Leeds and possibly York, and the London Midland Region main line from Euston to Birmingham, Crewe, Liverpool and Manchester will be electrified. The Eastern Region line now being electrified to Chelmsford was to be extended to Harwich, Clacton and Felixstowe. Suburban electrification was proposed for the King's Cross to Hitchin and Letchworth, the London, Tilbury and Southend, and the Enfield–Chingford–Hertford-East–Bishops Stortford lines; and electrification around Glasgow, recommended by the Inglis Report of 1951, was included.

All this work will be affected by the British Transport Commission's decision in March, 1956, to adopt as standard the 25 kV 50 c/s single-phase system, subject to the approval of the Minister of Transport. But the third-rail d.c. system is to be retained for the extension of the Southern Region services to Ramsgate, Dover, Folkestone and Hastings, which were also included in the plan.

(7.1.2) **Austria.**

Eight hundred and fifty-five route-miles, or 23%, of the total mileage carrying nearly 50% of all traffic has now been electrified at 15 kV single-phase 16⅔ c/s. The backbone of the electrified system is the great East–West route from Hegyeshalom, 35 miles from Vienna on the Hungarian frontier, to Bregenz on Lake Constance (527 miles). Electrification of this important route from Switzerland to Vienna began in 1919 with the Arlberg and Salzkammergut sections, and was completed in 1953 with the electrification between Amstetten and Vienna (97 miles).

The other main electrified route is the North–South line between Germany and Italy, completed in 1953 by electrification of the section from Villach to Tarvisio (17 miles), where connections are made with the Italian State Railways' electrified main line to Udine. The connection to Jugoslavia from Villach via the Karawanken tunnel was due for completion in 1955. In this year also the line between Passau and Wels, 51 miles, was equipped to facilitate through working from Frankfurt to Vienna via Nuremberg.

Planned extensions include the section from Amstetten to Eben, 10 miles from Bischofstofen, so providing a relief route to the East-West main line, especially between Linz and Wels. Electrification proposals for the country covering 50% of the system will be completed with the conversion of the southern main line over the Semmering Pass, Vienna–Bruck-an-der-Mur–Graz (131 miles) and the Bruck-an-der-Mur–Klagenfurt–Villach section (131 miles), by which time steam traction will be eliminated and the secondary lines operated by Diesel trains.

(7.1.3) **Belgium.**

Main-line electrification was initiated in 1935 on the 3 000-volt d.c. system over the 28 miles between Brussels and Antwerp. In 1949 the separate freight line between Brussels (Linkebeek) and Antwerp North (43 miles) and the Brussels–Midi–Charleroi (34 miles) were electrified. The building of the Brussels Junction Railway between Nord and Midi, brought into use in 1952, was allied with the electrification programme.

Electric working began on the Brussels–Ghent–Ostend line in June, 1954, and on the Brussels–Louvain and Denderleeuw–Alost sections in October, 1954. The electrification of the Ostend coastal area was completed early in 1955 with the conversions of the Bruges–Knocke and Blankenberghe branches. The Brussels–Liége section (62 miles) was completed in October, 1955, and the electrification of the heavily graded line from Brussels via Namur to Arlon on the Luxembourg frontier is to be finished in 1956. When this has been carried out, nearly 500 route-miles, or 16%, of the State railway system will have been electrified.

Arrangements are being made for through running with suitably equipped multiple-unit stock between Antwerp and Holland by the extension of the Belgian Railways 3 000-volt d.c. system to Roosendaal to link with the Netherlands 1 500-volt d.c. system.

(7.1.4) **France.**

The last progress review (1937) referred to the Marquet scheme, which was to connect the seaports of St. Malo and Nantes via Le Mans and Paris to the Eastern Frontier Railway via Château-Thierry and also to electrification between Le Havre and Marseilles via Paris. In fact, of the Marquet scheme only the section between Le Mans and Paris (132 route-miles) was completed in 1937, but considerable work was carried out by the former Paris–Orleans and Midi lines from Tours and Orleans to the Spanish frontier via Bordeaux and Toulouse. Electric working on the Séte-to-Nîmes section (48½ miles) began in 1947. Perhaps the most spectacular accomplishment has been the conversion of the Paris–Marseilles main line between Paris and Lyons (318 route-miles). The first stage from Laroche to Dijon was inaugurated in 1950, and the final section from Châlon-sur-Saône to Lyons was completed in June, 1952. The extensions from Macon and Lyons to Amberieu and Culoz linked up with the existing Culoz–Modane system. This made electric traction possible from Paris via Modane and Rome to Villa San Giovanni in Southern Italy, a distance of approximately 1 330 miles. Projected electrification in Savoy includes the lines to Geneva. All the electrification work noted above was installed on the 1 500-volt d.c. system, but investigations carried out by French engineers on the 50 c/s single-phase system resulted in the experimental equipment at 20 kV single-phase 50 c/s of the line Aix-les-Bains–Annecy–La-Roche-sur-Furon (48 miles). The voltage was raised to 25 kV in 1953, and the service was subsequently extended to Annemasse and St. Gervais. The 1 500-volt d.c. systems will be extended from Dijon to Dôle, but the 25 kV single-phase 50 c/s system will continue from Dôle to Vallorbe and from Frasne to Pontarlier. Success in the Annecy trials led to the decision to apply the 50 c/s system to the Valenciennes–Thionville line in Northern France, and the whole section, 225 route-miles, was completed in August, 1955. Work is proceeding westward on the extension to Lille and to the east from Thionville to Metz, Strasbourg and Basle.

The electrification of the following sections has been planned: Valenciennes–Somain, May, 1957; Somain–Longueau, Douai–Ostricourt, Ostricourt–Lens, October, 1957; Longueau–Paris, May, 1958; Paris–Longueau via Ormoy, 1959. Possible developments include the electrification on this system from Paris via Nancy to Reding on the Metz–Strasbourg section.

(7.1.5) **Germany.**

German railway electrification was developing on the 15 kV single-phase 16⅔ c/s system in three areas before the Second World War, in Bavaria, Silesia and Central Germany. Experiments with a frequency of 50 c/s were begun on the Hollenthal line in 1933, but a continuance of the existing 15 kV 16⅔ c/s system was reaffirmed in 1953. The conversion of the Hamburg suburban lines from 6·6 kV single-phase 25 c/s to 1 200 volts d.c. third-rail was begun in 1938, but was not completed until 1955. Much of the electric equipment of the lines in Eastern Germany was removed in 1945, but war damage and dismantling has been made good on the Halle–Kothern section, and it is probable that further sections of the Magdeburg–Leipzig lines will be

re-equipped. The bulk of the Federal Railways' electrification is in Würtemberg and Bavaria. By 1938, 728 route-miles had been converted in this area, largely made up of the Stuttgart–Munich and Regensburg lines to the Austrian frontier at Kufstein and Salzburg. In 1950 the Nuremberg–Regensburg section (62·5 miles) was converted, followed in 1954 by electric working between Nuremberg and Würzburg. In 1955 the extension from Bruchsal to Heidelberg was completed, bringing the total present electrified route of the German Federal Railway to over 1 200 miles, or 6% of the total. Planned work in the Ruhr and Rhine areas includes the sections Hamm–Dortmund–Essen–Düsseldorf, followed by the alternative route, Dortmund–Gelsenkirchen, Essen–Oberhausen–Duisburg. The Rhineland Palatinate Government has agreed to assist the Federal Railways' four-year conversion scheme of the Ludwigshafen–Mainz–Coblenz–Remagen lines. Projected extensions of electrification include the sections Würzburg–Aschaffenburg–Frankfurt and the connection of the Basle–Freiburg section to the Karlsruhe–Mannheim line. Further plans embrace connecting lines in the Frankfurt area and also the line between Remagen and Cologne.

The Federal Railways have long been interested in battery rail-cars, and in 1952 they put into service a new type. Each long car of light-weight construction has a 945 Ah lead-acid battery, giving an operating range of 155–186, or with a small intermediate charge, 248 miles daily. The total weight of the car is 55 tons; with a maximum speed of 56 m.p.h. they are considered profitable on secondary lines branching from electrified routes.

Trials of three prototype locomotives were begun in 1952 and resulted in orders for 195 mixed-traffic bogie type, confirming the trend away from the former rigid frame design. The E.10 type, an 80-ton B_0–B_0 locomotive, is continuously rated at about 4 500 h.p. 60 m.p.h., with a short-time capacity of 6 000 h.p.

An interesting standard-frequency electrification is that of the Rheinische Braunkolen Company, for which 56 twin 120–125-ton locomotives were introduced in 1954–55 for working between the coalfields and the power stations. The locomotives operate on a 6 kV single-phase 50 c/s system and have an output of $2 \times 2\,400$ h.p. at 16 m.p.h. with a starting tractive effort of $2 \times 44\,000$ lb and a maximum speed of 43 m.p.h. Fifty-three locomotives are fitted with synchronous motors driving 750-volt d.c. generators supplying nose-suspended motors through double reduction gears. The remaining three are rectifier locomotives.

(7.1.6) **Italy.**

Italy, with a standard 3 000-volt d.c. system, has the longest route-mileage of electrified lines in Europe, now totalling, with State and private ownership, 4 138 miles. Extensive damage sustained by the electrified sections during the war has been made good.

In 1951, electric working was introduced in the first section of the Messina–Palermo line, and the whole section (144 miles) was completed during 1955. Further electrification in Sicily is planned from Messina to Catania, and from Bisocca to Fiumetorto.

The work of converting the 3-phase electrification has been continued from time to time, and the 10 kV 3-phase 45 c/s Rome–Avezzano–Sulmona line, electrified in 1928–33, was changed over in 1950 to facilitate the extension of the d.c. electrification to Pescara. Work on the standard system is in progress between Pescara and Foggia, and Foggia to Bari. These sections form part of the great Bologna–Lecce line (496 miles), which follows the Adriatic coast to the heel of Italy and has already been electrified from Bologna to Ancona. In 1954 the Bologna–Ferrara section of the main line to Venice was equipped, and this was extended to Padua in 1955. Work is progressing on the section from Treviglio to Padua on the main Milan–Venice route.

(7.1.7) **The Netherlands.**

Steam locomotives have been replaced by electric or Diesel tractors on most services, and the modernization of the Netherlands Railways is practically complete. This is remarkable, since nearly all the 355 route-miles of electrified line and equipment in existence before the war was destroyed during hostilities so that the entire system has been virtually recreated since 1945. The decision to continue to use 1 500-volt d.c. traction was confirmed, and by 1950 all pre-war electrification services were restored and additional lines, including the Zwolle–Leeuwarden, Meppel–Groningen, Arnhem–Zwolle sections, were converted. To-day the route-mileage totals 828. Work in hand comprises the Eindhoven–Venlo line.

(7.1.8) **Norway.**

By 1936, 176 route-miles had been electrified on the 15 kV single-phase 16 c/s system, and this figure had risen to 565 route-miles by the end of 1950. The Norwegian Parliament sanctioned in 1952 the electrification of 750 miles of the State Railway system to be completed in 15 years. This will bring the total to 1 500 route-miles of electrified track, or 56% of the total system. The remaining mileage will eventually be operated by Diesel traction. At present, 790 route-miles have been electrified.

Through electric working between Oslo and Stockholm was facilitated by the electrification in 1951 of the Lilleström–Charlottenberg (71 miles) section via Kongsvinger. In 1953 the Lilleström–Hamar (66 miles), and in 1954 the Bergen–Voss (67 miles), lines were converted. Work in progress includes the Egersund–Stavanger section. Motive power on the State Railways totals 441 steam and 103 electric locomotives. It is anticipated that, with the elimination of steam, the total number of tractors, electric and Diesel, will be less than 300.

(7.1.9) **Portugal.**

Interest in electrification has been stimulated by hydro-electric development, and following the report of a Portuguese Railway mission, the electrification is being undertaken of the suburban line from Lisbon (Rossio) to Sintra (17 miles), and in two stages the Lisbon–Entroncamento–Oporto main line (242 route-miles). This work is to be carried out on the single-phase 50 c/s system.

(7.1.10) **Spain.**

Before the Second World War, approximately 288 route-miles of the Spanish National Railways were electrified. Most of this mileage, and also that of a number of privately-owned lines, was operated on the 1 500-volt d.c. system; but the 19 route-miles between Nacimiento and Gádor in Andalucía had been operated since 1911 on the 6 kV 3-phase 25 c/s system, and in 1955 was being extended to Almeria.

In 1951 the National Railways planned to electrify at 3 000-volts d.c. the main line from Hendaye on the French frontier to Algeciras (820 miles). Other electrification programmes have been announced from time to time, but financial difficulties have prevented their fulfilment.

Existing electrification is concentrated around Barcelona, Madrid and the industrial North West. In 1948 the Barcelona–Mataró section was electrified, and in the following year the first stage of the Ponferrada section in the Cantabrian Mountains from Brañuelas to Torre was put into operation at 1 500 volts d.c., and was extended to Ponferrada in 1954, and from Brañuelas to León in 1955, when the whole section was converted to 3 000 volts d.c. The 39-mile Busdongo–Ujo section, electrified at 3 000 volts d.c. in 1924, was extended to Gijon (35 miles) in 1955, and work is proceeding on the conversion between Busdongo and León

(33 miles) to link with the Pontferrada electrified line. For these heavy-mineral lines, 60–3 600 h.p. (1-hour rating) 118-ton C_0–C_0 locomotives were built in Great Britain. They have a continuous tractive effort of 30 360 lb at 36 m.p.h., and regenerative braking is provided. The heavily graded section with numerous tunnels from Santander on the North Coast to Reinosa (55 miles) was converted to electric working in 1954.

Possible further electrifications include the extension of the Barcelona–Mataró section to Empalme, the junction with the line to the French frontier at Port-Bou. Electrified mileage in Spain now totals 1 095 route-miles, including approximately 350 route-miles of private lines.

(7.1.11) **Sweden.**

The electrified railway system of Sweden runs from the Norwegian border of the Narvik iron-ore line to Lulea (279 miles), and from Boden, near Lulea, to Stockholm. From Stockholm, all important lines are now electrified to the west and to Trelleborg in the southernmost tip of the country. In 1947 the State purchased the private Bergslagen railway, which had in the previous year completed the electrification of the Gothenburg–Gavle line (354 route-miles). Electric traction at 16 kV single-phase 16⅔ c/s was used for over 4 100 route-miles, including some 300 route-miles of private railways, giving Sweden a high place in world railway electrification.

(7.1.12) **Switzerland.**

There are over 3 100 route-miles of electrified lines in Switzerland, both State and privately owned. Of the Swiss Federal lines, 97% are equipped on the 15 kV single-phase 16⅔ c/s system. The Rhaetian Railway, of metre gauge, the most extensive of the independent systems (245 route-miles), is completely electrified. This also applies to the Berne–Lotschberg–Simplon Railway, which has an importance far in excess of its comparatively small system.

Recent conversions have been the Winterthur–Bauma–Wald line in 1951; the Saignelegier–La-Chaux-de-Fonds and Saignelegier to Glovelier lines in 1952. To link up with the French National Railways, the electrification of the 10-mile section from La Plaine to Geneva (Cornavin) will be electrified at 1 500 volts d.c., and the French approach to Basle at 25 kV single-phase 50 c/s from the Lille–Valenciennes–Strasbourg line is to be accommodated by alterations to the existing Swiss 15 kV single-phase 16⅔ c/s system. In the same way, the electrification between the Badischer and the Hauptbahnhof and Muttenz yards at Basle will continue the German Federal Railways' Freiburg–Basle electrification.

(7.1.13) **The U.S.S.R.**

Prior to the Second World War, Russia had 1 040 miles of electrified line, representing about 2% of the total system. Latest reports indicate that the electrified mileage is now about 4%, mainly on the 3 000-volt d.c. system. Two sections, Kalinen–Boogoje and Ozherelye Pavelets, have been electrified at 22 kV single-phase 50 c/s. A number of lines around Moscow have been electrified, and considerable extensions have been made to electric working over the heavily graded lines in the Caucasus. The electrification between Nikipol and Dolghintsevo in the Southern coalfields was completed in 1948 and was later extended to Zaporozhe. Hitherto, only suburban lines or short main-line sections with heavy traffic or steep grades have been electrified. But the conversion of the Trans-Siberian line between the Urals and Kuznetzk, some 1 500 miles, is reported to be in progress. An extensive electrification has been planned of the local lines in the areas round Leningrad, Kiev, Baku, Kuibyshev and Omsk, while in November, 1955, it was announced that 6 200 miles of line between Moscow and Vladivostock were to be electrified.

(7.2) Asia

(7.2.1) **Ceylon.**

Hydro-electric development has stimulated interest in railway electrification, and proposals have been made for the electrification of the Colombo suburban system and the main line from Colombo to Kandy with its heavy gradients; also the line from Colombo to Maho.

(7.2.2) **India.**

No electrification was undertaken between 1936 and 1954, but then work began on the former East Indian Railway from Calcutta (Howrah) to Burdwan via Bandel and the branch from Sheoraphuli to Tharakeshwar (262 single-track miles). This is the first of six phases covering the suburban lines of the former East Indian and East Bengal Railways from Howrah and Sealdah, and has been scheduled for completion in 1957. Long-term proposals cover the electrification of the Eastern Railway's main line from Burdwan to Moghalsarai via the Grand Chord, one of the busiest traffic routes in India. While the Bombay and Madras electrifications are on the 1 500-volt d.c. system, the Calcutta lines are to be at 3 000 volts d.c., with a supply from the Damodar Valley Corporation grid. The extension of the southern electrified system from Tambarum to Villupuram has also been approved.

During 1953 and 1955 additional up and down tracks between Bandra, Andheri and Borivili on the Western Railway, and third track between Madras (Egmore) and Tambaram on the Southern Railway, were electrified.

In 1951, 24 4-car light-weight multiple-unit sets were supplied to the Western (formerly B.B. and C.I.) and Central (formerly G.I.P.) Railways Bombay suburban electrification. These are over 25% lighter than the original stock built for these lines. Seven C_0–C_0 123-ton 3 600 h.p. British-built locomotives were put into service on the Bombay–Poona and Igatpuri line in 1953. Twelve locomotives of a similar type, but operating on 3 000 volts d.c., have been ordered for the Calcutta–Burdwan electrification.

(7.2.3) **Japan.**

According to published information Japan has a greater length of electrified route and track mileage than any other country in the world. Although the Japanese National Railways have 1 165 route-miles electrified, the private companies have such a large proportion of electrified track that the total for the whole country is 6 563 route- and 9 026 track-miles. The 1 500-volt d.c. system predominates.

In 1947, the 167 miles from Ueno to Nagaoka were electrified. Extensions of the main Tokaido line have been made from time to time, and the electrification between Numazu and Nagoya, completed in 1953, permits electrical operation between Tokyo and Nagoyo (230 miles). The section from Nagoyo to Maibara (50 miles) was scheduled for completion in 1955. Extensions are planned from Maibara to link up with the existing Osaka electrified lines and on to Himeji and Okayama. It is also proposed to electrify two routes north from Tokyo for 218 miles on the Tohoku main line and 227 miles on the Joban line from Ueno to Sendai. Tests are being carried out of the single-phase 50 c/s system on the line between Sendai and Sakunami (18 miles).

The desire to improve freight train timings and to eliminate delay to passenger trains has led to the introduction of locomotives of the EH.10 type. These are B_0–B_0 + B_0–B_0 123-ton 3 300 h.p. 3 ft 6 in gauge locomotives with a maximum speed of 52 m.p.h.

(7.2.4) **Turkey.**

Contracts have been placed for the electrification of the Istanbul suburban lines on the 25 kV single-phase 50 c/s system. The first section from the Sirkeci terminus to Soguksu (17 miles) on the European side of the Bosphorus, with 18 3-car multiple-units sets, was completed in 1955. A set comprises two motor cars, each with one power bogie, and a central trailer car. The two self-ventilated motors in each power bogie are axle-hung and connected permanently in parallel, and are continuously rated at 325 h.p., 240 volts. The line supply at 25 kV is taken through an air-blast circuit-breaker to the main transformer. The traction motors are supplied from a camshaft control equipment giving various tappings on the transformer secondary winding. Knorr wheel-slip-detector relays are fitted. Three 2280 h.p. 80-ton B_0–B_0 locomotives were also built for this service.

Further proposals include the electrification on the Asiatic side from Haydarpasa to Zongouldak on the Black Sea via Ankara, and for an underground railway in Istanbul.

(7.3) Africa

(7.3.1) **Belgian Congo.**

The single-track 3 ft 6 in gauge section of the Bas Congo au Katanga Railway between Jadotville and Tenke (64 miles), near the Northern Rhodesian frontier, was electrified on the 25 kV single-phase 50 c/s system in 1951, and was extended from Tenke to Kolwezi (62 miles) in 1953. The further extension to Elizabethville (84 miles) is in hand. The development of hydro-electric power facilitated the conversion which had been forced by increased traffic demands for heavier trains at higher speeds in a country where the importation of coal and oil is costly and difficult.

Twelve B_0–B_0 locomotives, axle loading 18·5 tons, 1680 h.p. (1-hour rating), capable of hauling 550-ton trains at 28 m.p.h. up 1 in 80, were initially provided. The main equipment of these locomotives comprises a step-down transformer with variable tappings on the secondary side and four double-armature single-phase commutator motors.

(7.3.2) **South Africa.**

It is now planned to eliminate steam traffic in and around Capetown, Durban, Pretoria and the Reef. The Natal system from Durban, which extends to Volksrust and Harrismith, totals 427 route-miles. In the Witwatersrand (Reef area) some 206 route-miles have been electrified, and ultimately it is proposed to link this system with the Natal Railway at Volksrust via Germiston. The Capetown–Simonstown line (22 miles), electrified in 1928 at 1 500 volts d.c., has been converted to 3 000 volts d.c. to conform to the standard of the Union. The electrification of the main line from Capetown to Touws River (149 miles) was completed in May, 1954, bringing the total electrified route-mileage of the country to 861.

Seventy-two 3 000-volt d.c. motor-coach equipments, manufactured in Great Britain, were recently introduced on the Cape Western suburban system, together with 40 class 4.E 155-ton C_0–C_0 locomotives of 3 030 h.p.

The latest electric locomotives on order for the Natal main line comprise 60 class 5.E 83-ton B_0–B_0 locomotives of 2 000 h.p. with a maximum speed of 60 m.p.h.

(7.4) America

(7.4.1) **Argentina.**

The first long-distance electrification, that of the Argentine Transandine line, part of the General San Martin Railway, has been proposed. This will be made possible by the building of two hydro-electric stations at Mendoza. One hundred and twenty-five miles of metre gauge are to be equipped, with branches to Mendoza to link with the Chilean Transandine line already electrified at 3 000 volts d.c. The system to be adopted is 27 kV single-phase 50 c/s.

Further proposals include the electrification of the Buenos Aires–Rosario line, the Córdoba Hill system, the Tucumán suburban lines and from Tucumán to La Quiaca on the Bolivian frontier.

(7.4.2) **Brazil.**

The Paulista—a private 5 ft 3 in gauge line under the supervision of the Federal and São Paulo State Governments—now totals 451 route-miles on the 3 000-volt d.c. system from Jundiai to Rincão and from Itirapina to Bauru. The Bauru–Cabralia section is under conversion. At Jundiai it connects with the Estrada de Ferro Santos a Jundiai (formerly the São Paulo Railway), which was electrified for 87 miles to Maua between 1950 and 1952. It is ultimately planned to complete the electrification to Santos on the coast. Prior to 1939, the Central Railway had 44 miles of electrified line from Rio de Janeiro to Bangu and Nova Iguacu. The extension of electrification has proceeded steadily, having reached Santa Cruz in 1945 and Barra do Parai in 1949, and now totals 194 route-miles. Orders for 100 motor coaches and 100 trailers complete with electrical equipment, and a further 100 car sets of electrical equipment for coaches to be built in Brazil, were placed with British manufacturers in 1954. The metre-gauge Sorocabana has electrified over 340 miles on the 3 000-volt d.c. system since 1944, and extensions have been planned on the section Sorocabana–Bernardino-de-Campas–Assis–Presidente-Prudente and Presidente-Epitacio. In 1950, 14 metre-gauge mixed-traffic B_0–B_0 1 080 h.p. (1-hour rating) locomotives were built in Great Britain for the Rede Mineira de Viaçao, and 10 similar locomotives of the same manufacture for the Paraná–Santa Catharina Railway. The Rede Mineira de Viaçao electrified the 152 route-miles from Divinopolis to Bello Horizonte in 1953 on the 3 000-volt d.c. system. The electrification by the Eastern Railways of Brazil of the suburban lines of Salvador, capital of Bahia, were included in the 1954 Brazilian development programme.

(7.4.3) **Canada.**

The electrification of the Toronto Subway, opened in March, 1954, on the 600-volt d.c. system, presented several interesting features. It was $4\frac{1}{2}$ miles long on the 4 ft $10\frac{7}{8}$ in gauge. The rolling stock had several unusual features: each car was a motor car with a single driving end, and each bogie carried a pair of Cardan-shaft-drive traction motors with high-ratio right-angled gearing. Trains are made up in pairs of cars up to 8 and accelerate at 2·3 m.p.h./sec on the level. Braking is preset to give a maximum retardation of 3·0 m.p.h./sec.

(7.4.4) **The United States.**

The tremendous development of the Diesel-electric locomotive in the United States has not only put a stop to main-line electrification but has superseded electric working on some lines.

An interesting case was the reversion of the Norfolk and Western Railway to steam working after 35 years of electrical operation, following realignment and the building of the new double-track Elkhorn Tunnel. This is the only major United States railway entirely under steam operation; in 1954 it introduced a 4 500 h.p. 586-ton steam turbo-electric locomotive. Electric working through the Detroit River tunnel, comprising in all 28 track-miles, begun in 1910, was abandoned in 1953. Ventilating plant has been installed to clear Diesel fumes from the tunnels. The 3 000-volt d.c. 'smoke abatement' electrification installed in 1930 for the Cleveland Union terminals has been displaced, and trains are now all Diesel worked. The

Sacramento Northern has reduced its electrified route-mileage by over 70 route-miles.

Four twin-unit B_0–B_0 + B_0–B_0 446-ton motor-generator locomotives, maximum tractive effort 260 000 lb, maximum speed 50 m.p.h., were put into service in 1949 on the 11 kV single-phase 25 c/s Virginian Railway for hauling heavy coal trains. Interest in rectifier locomotives resulted in the introduction on the Pennsylvania Railway in 1949 of a motor coach with four ignitrons, and in 1952 of two twin-unit ignitron locomotives. In 1954 the first of ten ignitron locomotives of 4 000 h.p. were under manufacture for the 11 kV single-phase 25 c/s New York, New Haven and Hartford main line, which changes over to 660-volt d.c. third-rail in the city terminal area. This railway has also recently introduced 100 rectifier-motor coaches with the same facility. The water-cooled ignitrons are resiliently mounted on the under-frame. Change-over from 600 volts d.c. rail to 11 kV overhead is carried out at about 30 m.p.h. Shoegear is raised pneumatically, and the correct connection of equipment is governed by voltage relays. The Virginian Railway has recently ordered twelve 3 300 h.p. C_0–C_0 single-anode-rectifier locomotives.

Motive power on the Great Northern 74-mile electrified section from Wenatchee and Skykomish, including the Cascade tunnel, is under review. The alternatives are complete Diesel working, Diesel working retaining the electrified tunnel section, or extension of the electrification, perhaps as far as Seattle (84 miles).

(7.5) Australasia

(7.5.1) Australia.

In 1954 the first section of the heavily graded Gippsland main line in Victoria from Dandenong to Warragul, 61 miles from Melbourne, was converted, and work is continuing on the Warragul–Traralgon section, a further 37 route-miles. The electrification will facilitate the handling of raw brown coal and briquette traffic between Melbourne, Moe and Morwell. The maximum gradient is 1 in 50, and twenty-five 2 400 h.p. C_0–C_0 locomotives have been ordered, with tractive efforts of 48 000 lb (starting) and 28 200 lb (1-hour rating).

In New South Wales, extension of the suburban system from Paramatta to Blacktown was completed in 1955, and the electrification of the Sydney–Lithgow (97 miles) main line to facilitate the handling of heavy coal traffic over the Blue Mountains is due for completion in 1957. Forty 3 850 h.p. locomotives and ten 8-car multiple-unit sets have been ordered for this section.

(7.5.2) New Zealand.

The problem of suburban working in and around Wellington was eased by the electrification of the Wellington–Johnsonville line in 1938 and the Paekakariki line in 1940. In 1953 the first section of the Hutt Valley line was electrified, and was completed to Upper Hutt in 1955, giving Wellington a modern suburban service of some 50 route-miles. The track gauge is 3 ft 6 in, and all systems are at 1 500 volts d.c. In 1952, seven 1 800 h.p. 75-ton articulated mixed-traffic British-built locomotives of the B_0–B_0–B_0 type were introduced. To facilitate wayside shunting, these locomotives have long-time-rated resistances. Proposals for electrification in and around Auckland have not yet found justification.

(8) ACKNOWLEDGMENTS

Acknowledgment with thanks is made for assistance from several quarters, including railway electrical engineers and various manufacturers, and for information derived from the technical Press, especially the *Railway Gazette*.

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SWITCHGEAR

A Review of Progress

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SUMMARY

In British switchgear, development during the period under review has been directed mainly towards the improvement of interrupting performance, measured by reliability and speed of interruption of short-circuits, and by the prevention of over-voltages when disconnecting open-ended lines or small reactive currents. It has also been directed towards reducing the size and cost of switchgear and the buildings in which indoor gear is mounted.

The techniques of oil, air-break and air-blast interruption, and of multi-break design, with various forms of voltage division, have all been exploited to assist in achieving these aims. There is now little room for further reduction in the minimum size of switchgear for a given voltage, but the MVA rating for the smallest frames, already doubled in this period, will no doubt continue to increase in the future.

The upper limit of MVA has increased seven times in the period under review, and there are no obvious limitations to further progress; it is to be expected that the MVA rating available in circuit-breakers of British design will continue to exceed those required on contemporary networks.

(1) INTRODUCTION

Reviews of progress in the field of switchgear, that have appeared in the *Journal*, have been concerned with metalclad equipment[1] and high-voltage circuit-breakers.[2] The present review covers the field of indoor and outdoor alternating-current circuit-breakers and associated metalclad structures, with special reference to progress made since 1945.

The concentration of effort on development and testing of British circuit-breakers has continued since the war with increasing momentum, largely as the result of the activities of the six large short-circuit testing plants now available. These test plants are associated for the technical control of testing technique and certification of short-circuit ratings in the Association of Short-Circuit Testing Authorities (A.S.T.A.) founded in 1938. The testing codes issued by this body elaborate the basic specifications drawn up by the British Standards Institution, and fill in much detail found desirable as the result of experience.

This period has seen metalclad switchgear consolidate its position as the standard British equipment for indoor duty up to 33 kV, offering more MVA capacity per cubic foot of substation volume than previously, despite the more stringent testing to which these designs are now subjected. Air-break gear has made marked inroads at the lower operating voltages on the monopoly previously held by oil circuit-breakers, both being used in conjunction with metalcald boards. At the highest voltages, air-blast equipment has entered the field in competition with outdoor oil circuit-breakers, and above 132 kV it is numerically in the majority. The versatility of the oil circuit-breaker in its various forms has, however, enabled it to be produced to meet the greatly increased ratings now required, and the art is perhaps too fluid to draw final conclusions as to the extent to which air and air-blast designs will supersede oil equipments in the future.

In a review of this nature, it is not possible to refer to every type available; an attempt has been made to discuss the development exhibited in current British practice for the most important types of duty and to illustrate some typical designs and those of special technical interest.

No review of British switchgear would be complete without reference to the activities of the British Electrical and Allied Industries Research Association, which has continued to advance the background of theoretical knowledge of arc-interruption phenomena and network characteristics affecting circuit-breaker performance.

(2) SPECIFICATIONS CONTROLLING THE DESIGN OF BRITISH SWITCHGEAR

(2.1) British Standards

There are a number of British Standards applying to switchgear, but B.S.116, controlling the short-circuit testing and general design requirements for oil circuit-breakers, reflects most closely the development and progress in the art. This Standard was first issued in 1923; it was revised in 1929, in 1937, and again in 1952. Among the more important changes are the extension in range of breaking capacities and voltages, which now include 275 kV, the introduction of impulse testing for outdoor switchgear, an increase in through-current short-circuit test duration from one to three seconds, and a differentiation in permitted temperature rise between silver-plated and plain copper contacts in oil or air, reflecting the more stable character of silver-plated components.

Although not directly applicable to air-break and air-blast circuit-breakers, for which categories specifications are in preparation, B.S.116 is, in practice, used for the testing of these types, with appropriate modifications and A.S.T.A. codes.

B.S.116 bases the MVA breaking-capacity rating on symmetrical current, and British practice is to assign total-current ratings 25% higher.

In comparing British and American ratings, it should be noted that the latter are normally based on total current, with a variable ratio between symmetrical and total current. Simple conversion of rating from one system to the other is therefore impossible. As total current is often the principal limitation in circuit-breaker performance, the breaking-capacity rating of many British designs can be raised by 25% in terms of MVA, based on the American system.

(2.2) A.S.T.A. Rules

The A.S.T.A. rules can be divided into two classes: first, rules which interpret the British Standards and which, after experience, may be incorporated in British Standard revisions; secondly, rules for testing equipment for which there is no adequate British Standard and for controlling additional test duties introduced to meet particular requirements of h.v. transmission systems.

In the first of these two classes are the rules which deal with assessment of performance under the following subject headings: evaluation of oscillograms, emission of gas and oil, failure to trip, damage to operating mechanisms and tank linings, and the burning of contacts.

Furthermore, the necessary requirements for proving the

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making capacity of circuit-breakers have been more completely specified in the A.S.T.A. rules than in B.S.116: 1952 or I.E.C. 56/1.

In the second class, the rules can be placed in three groups as follows:

(*a*) Rules for testing those types of switchgear for which there are no approved specifications.
(*b*) Rules for the unit testing of circuit-breakers.
(*c*) Rules for additional tests to meet special requirements.

The rules in group (*a*) follow the pattern of B.S.116: 1952 as far as possible.

Those in group (*b*) cover the testing of circuit-breakers with a rating exceeding the test-station output, but which can be subdivided into a number of unit interrupters, as is the trend in design. In this case, the A.S.T.A. rules are more in the nature of a basic guide, and the number of test duties can vary considerably, depending on the type and specific design of the circuit-breaker. These tests, in particular, have added considerably to the effectiveness of the short-circuit testing technique for large circuit-breakers. The A.S.T.A. rules require that the validity of unit testing shall be confirmed by appropriate voltage-division measurements; for some types of circuit-breaker they require proof of the distribution of arc-extinguishing fluid between the several breaks.

Group (*c*) includes some of the extra test duties that may be necessary when testing certain classes of high-voltage large-capacity circuit-breakers. The rules for the testing and certification of circuit-breakers fitted with auto-reclosing mechanisms come in this group. Additional making tests are required to prove that the circuit-breaker can withstand the effect of prearcing at high voltages.

The resulting test procedure has therefore become far more elaborate and searching, not only as regards checking the range of performance investigated, but also in respect of the quality of performance afforded. The extent of testing required on a large circuit-breaker under a combination of British Standard and A.S.T.A. techniques has risen from two tests comprising a single B-2-MB duty in 1929 to five 3-test duty cycles in 1937, and to the present condition which requires approximately 40–50 individual short-circuit tests for comprehensive certification of a large circuit-breaker. The typical distribution of these testing requirements is shown in Table 1.

(2.3) Standardization of Operational Features

A new aspect of British switchgear standardization has bee introduced as the result of the nationalization of the electrica generation and distribution industry by the setting-up of th Central Electricity Authority and Area Boards. These bodie in collaboration with the British Electrical and Allied Manu facturers' Association have established a Joint Switchgear Sub Committee whose terms of reference are to discuss aspects o switchgear standardization outside the scope of the British Stand dards, with the object of drawing up agreed specifications whic will form the basis of the purchasing specifications of the C.E.A and Area Boards. Through this channel a considerable measur of standardization of operational features has been and is bein introduced; this affects more especially such functions as inte locking, earthing, control, protection, instrumentation an facilities for transportation and easy erection, together wi selected preferences chosen from the British Standard ratin available. Although intended as standards for the nationalize power industry, there is a growing tendency for other users t adopt them.

(3) INDOOR SWITCHGEAR

(3.1) Foreign Practice

On the Continent of Europe, the usual practice is to empl open-type cellular gear incorporating low-oil, air-break c forced-blast air-break circuit-breakers, the air-break units be primarily employed for small breaking capacities and the low voltages. There is a limited production of air-break circui breaker equipment with metalclad enclosure up to 15 k 500 MVA. The dead-tank oil circuit-breaker is not representat of general practice, but there are in production a few range incorporating such circuit-breakers in metalclad enclosures.

In America, dead-tank oil circuit-breakers embodied in meta clad structures represent a falling percentage of new installatio but they are still significant in number. The trend is towards th air-break circuit-breaker mounted in air-insulated sheet-ste metalclad draw-out structures for ratings up to 500 MVA 15 kV. For higher indoor ratings, air-blast designs are increa ingly superseding oil circuit-breakers, and are available up 2 500 MVA at 15 kV and 5 000 MVA at 69 kV (American rating

Table 1

TYPICAL SCHEDULE OF PROVING TESTS FOR A HIGH-VOLTAGE CIRCUIT-BREAKER WITH A LARGE SHORT-CIRCUIT CAPACITY AND HAVING 4 BREAKS IN SERIES PER POLE

No. of tests	Duty	Proportion of breaker	Percentage of rating		Purpose of tests
			Current	Voltage	
3	B	Whole	10%	100%	British Standard series
3	B	Whole	30%	Max. available	British Standard series
3	B	Whole	60%	Max. available	British Standard series
3	B	Whole	100% (symmetrical)	Max. available	British Standard series
2	M	Whole	100%	Max available	British Standard series
3	B	Whole	100% (asymmetrical)	Max. available	British Standard series
1	Short time	Whole	100%	As convenient	British Standard series
3	B	Whole	Max. available	100%	Voltage distribution
3	B	Half	100%	Max. available	Voltage distribution
2	M	Whole	Max. available	100%	Voltage distribution
3	B	Half	30%	50%	Unit tests
3	B	Quarter	60%	25%	Unit tests
3	B	Quarter	100% (symmetrical)	25%	Unit tests
3	B	Quarter	100% (asymmetrical)	25%	Unit tests
2	M	Quarter	100%	25%	Unit tests

(3.2) British Practice

The stringent British Home Office requirements as regards safety to personnel are reflected in British circuit-breaker practice. They have had their influence in rendering the open-type cubicle equipment obsolete at lower voltages, and have increased continuously the degree of interlocking considered essential in metalclad designs. This influence, together with the increased cost and space requirements for air-break gear, has until recently concentrated development on oil-immersed dead-tank metalclad equipment throughout the range of indoor service requirements. Continuity of development and testing over a long period has resulted in a high degree of reliability and safety, and the dead-tank class of gear represents the major demand for indoor equipment from 3·3 to 33 kV, whether incorporated in air-insulated, compound-insulated or oil-insulated metalclad structures. A number of installations of this type have also been built for 66 kV service. In the period under review, however, air-break circuit-breakers mounted in air-insulated sheet-steel metalclad enclosures have been developed. These have been designed for 440 volts and 3·3 kV, and they are extensively used in installations where the advantages of air-break gear, such as freedom from risk of oil fire and reduction in contact maintenance, can outweigh disadvantages, such as increased space or cost and some reduction in dielectric security arising from increased risk of moisture absorption.

Within the last few years, a new trend has emerged in which both 66 kV and 132 kV outdoor equipments are housed indoors in order to protect them from atmospheric pollution or to save space. These installations can be either of normal open-type lay-out with conventional isolators, or arranged in fully segrated compartments with swinging-bushing through-wall isolators.

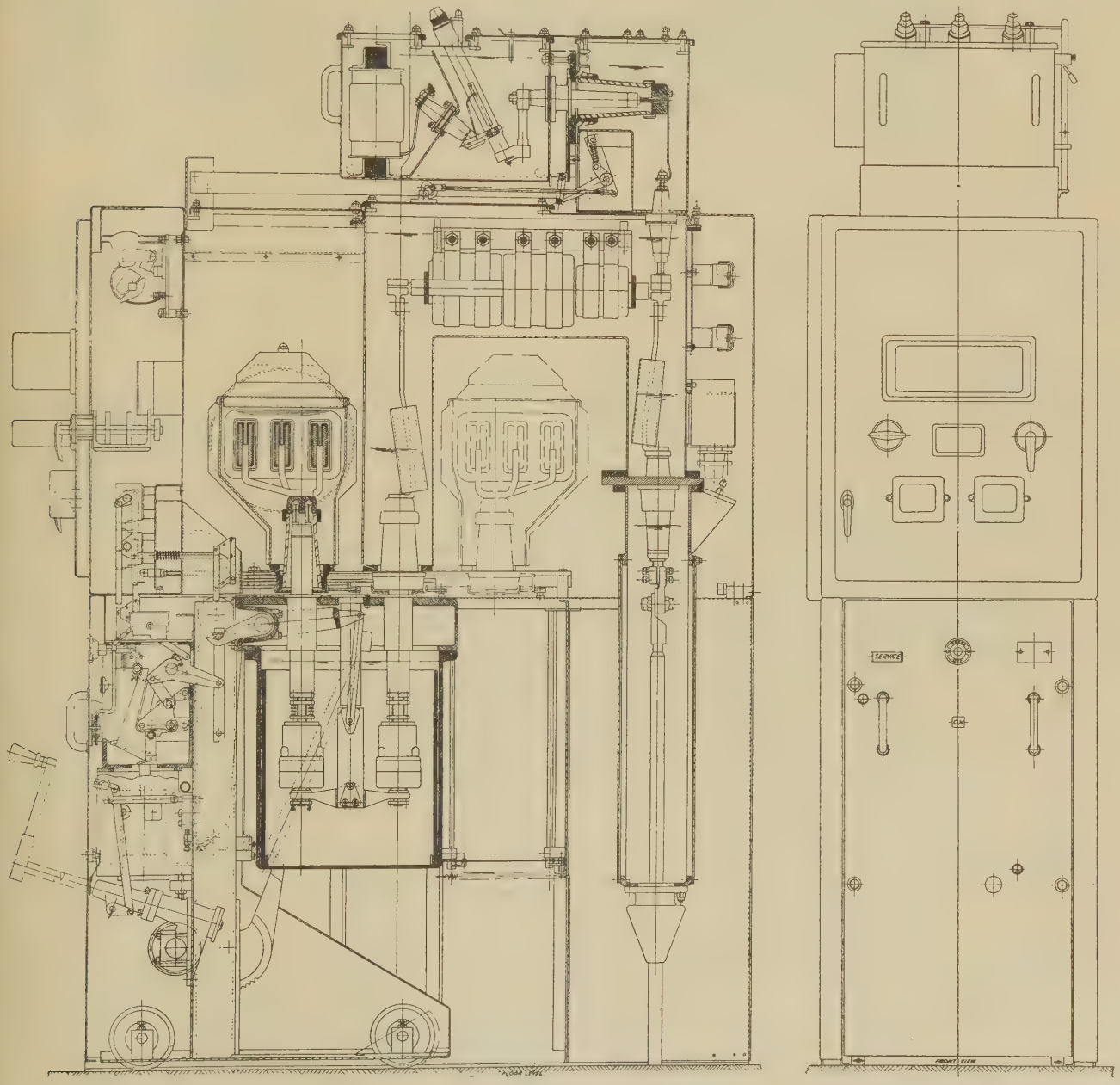


Fig. 1.—Air-insulated 11 kV 500 MVA metalclad unit with double-break vertical drop-down oil circuit-breaker.

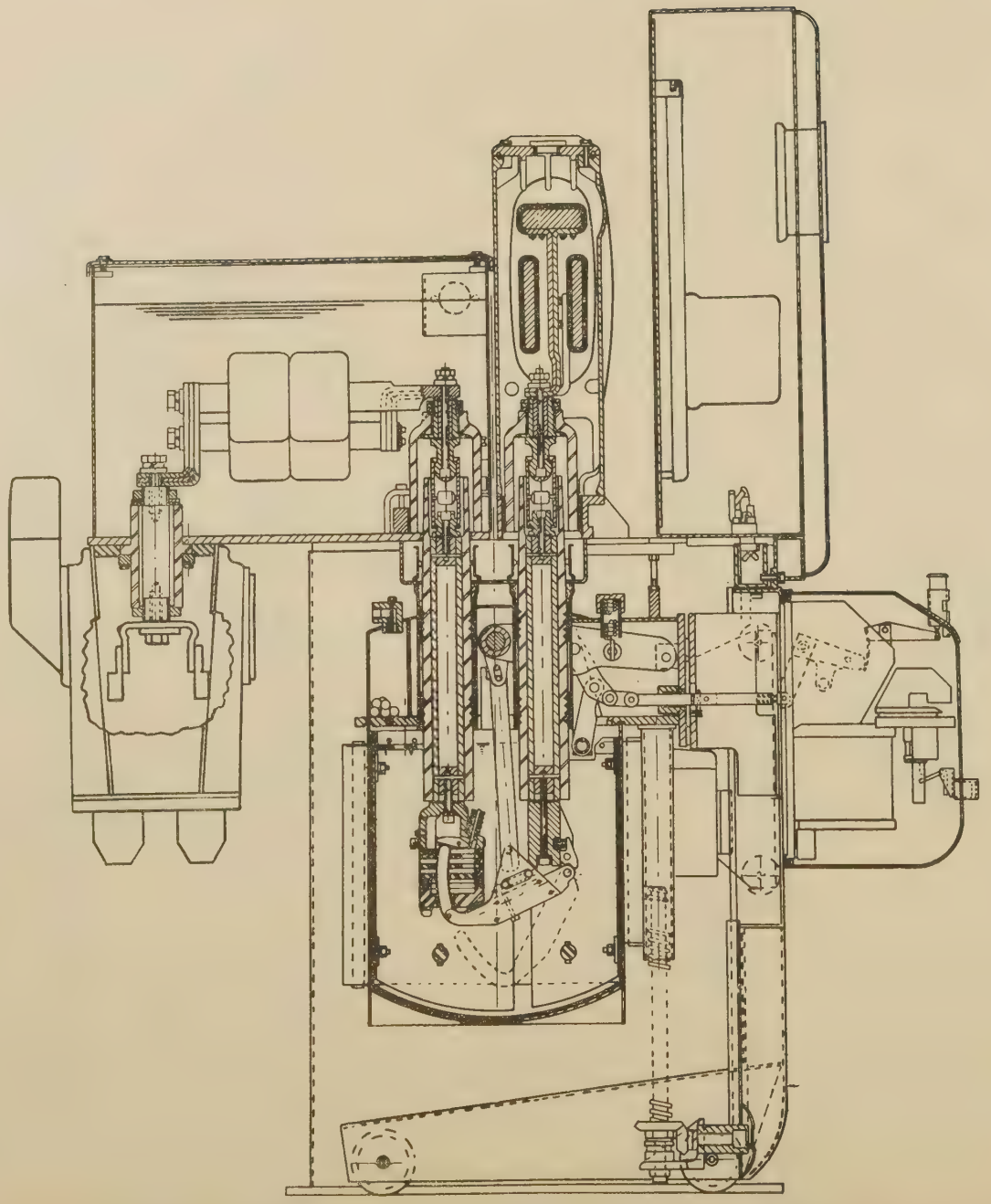


Fig. 2.—Air-insulated 11 kV 250 MVA metalclad unit with vertical drop-down single-break oil circuit-breaker.

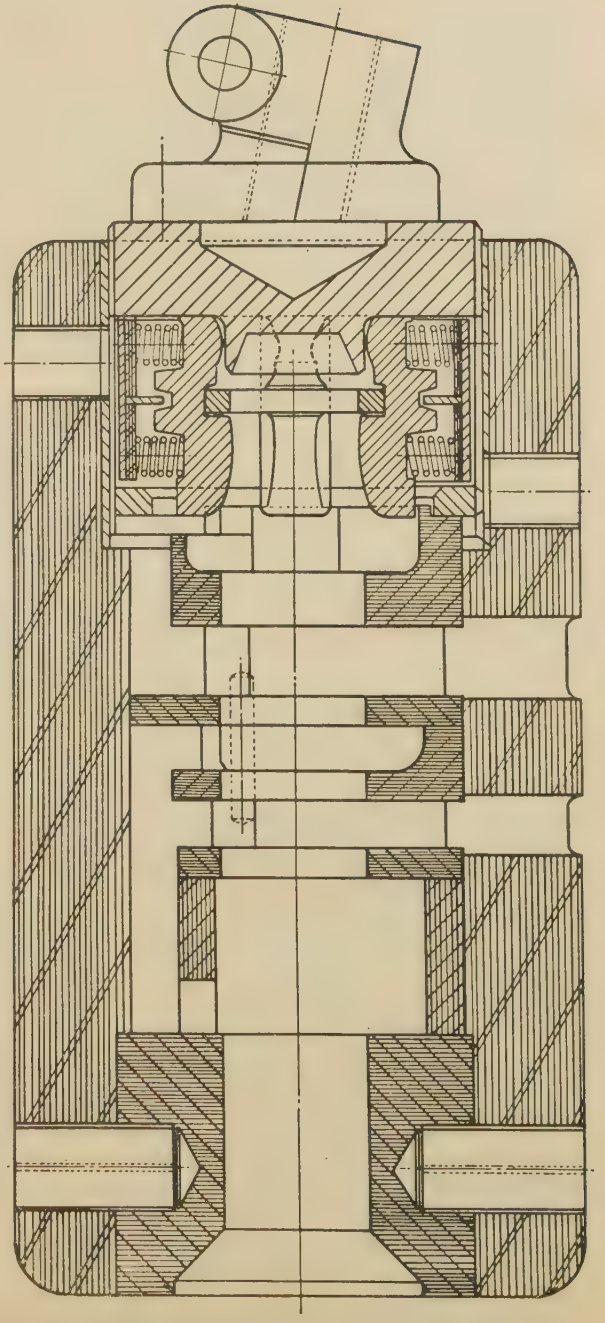


Fig. 3.—Typical 33 kV 1 000 MVA interrupter.

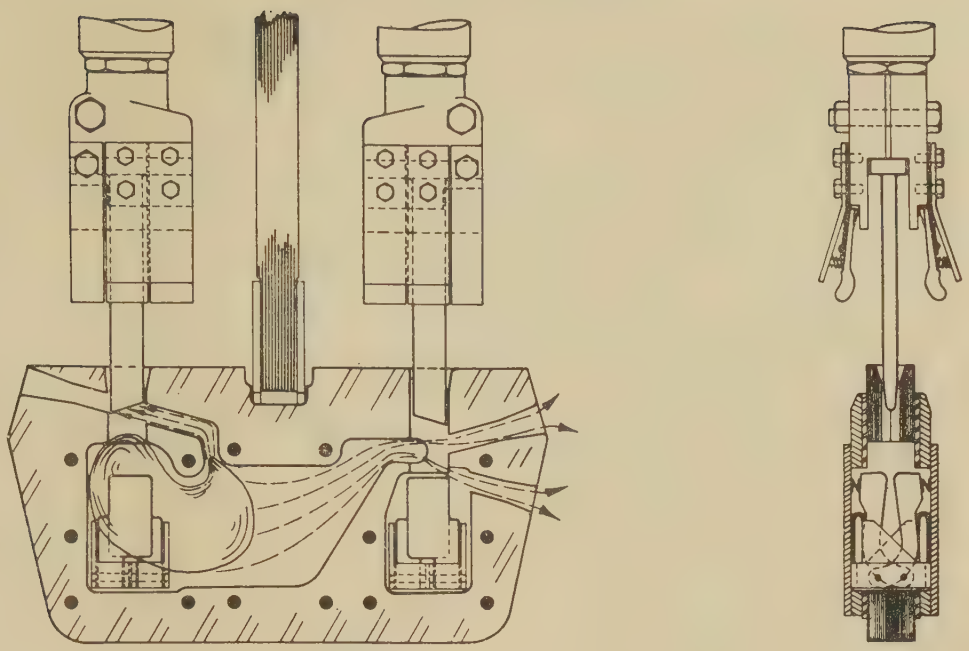


Fig. 4.—Typical cross-blast interrupter arranged as part of moving component of circuit-breaker.

Although both metalclad units and this new form of open construction are available for service at 66 kV, the open type has made the cost and development of modern 132 kV metal-clad equipments uneconomical, and no such designs are now available.

(3.2.1) **Indoor Oil Circuit-Breakers.**

The plain-break oil circuit-breaker has become virtually obsolete, except at the lowest ratings, such as 25 MVA at 440 volts, or 75 MVA at 3–11 kV, where the simplicity of construction and the relatively easy duty warrant its retention.

The extensive and continued use of oil circuit-breakers in Great Britain is based principally on the consistency and safety obtainable with arc-control devices; these are now in general use at 6·6 kV and 150 MVA and at all higher voltages and breaking capacities; before the war their use commenced at about 350 MVA. The number of breaks employed is determined more by economic and layout considerations in the design than by the relative merits of single- or double-break interruption within the ratings usually required for indoor service. Typical double- and single-break arrangements for 11 kV duty are shown in Figs. 1 and 2. Circuit-breakers of this general class now afford total-break-time performances of the order of 3–5 cycles, as compared with 5–10 cycles prevailing prior to 1939. This improvement has been brought about by a number of factors, such as the more general use of butt contacts, by the more extensive use of arc-control devices, by detailed improvements in these, and by the design of new high-speed release mechanisms appropriate to the performance provided by the arc-control and contact systems with which they are associated.

Arc-control devices are all of the cross-blast, as opposed to the axial-blast, type, varying in the extent to which materials such as fibre, pressboard, mouldings and impregnated wood are subject to arcing, and varying also in the degree of venting. Both "high pressure" and "low pressure" designs are in production. Fig. 3 is a typical design for 33 kV service.

A recent variation is to reverse the normal procedure and mount the interrupter assembly on the moving component of the circuit-breaker. Fig. 4 is representative of this class of construction, and enables the two arcs in a single interrupter device to interact on each other and assist in the reduction of the duration and length of the arc.

(3.2.2) **Indoor Air-Break Circuit-Breakers.**

The air-break circuit-breaker has made extensive progress both in design and in extent of use in the period under review. Introduced before the war at 440 volts, such designs for ratings of the order of 25 MVA have become the basic standard of a number of manufacturers. The air-break circuit-breaker at this voltage employs either asbestos-base or ceramic arc chutes; at heavy currents it limits arc duration to the order of one half-cycle, and therefore requires the minimum of contact maintenance. Development in this field has been concentrated on simplification and space reduction; the absence of oil permits the mounting of several units above one another in a single compartment.

Since 1945, 3·3 kV 150 MVA air-break circuit-breakers have come into extensive use, primarily for power-station auxiliaries,

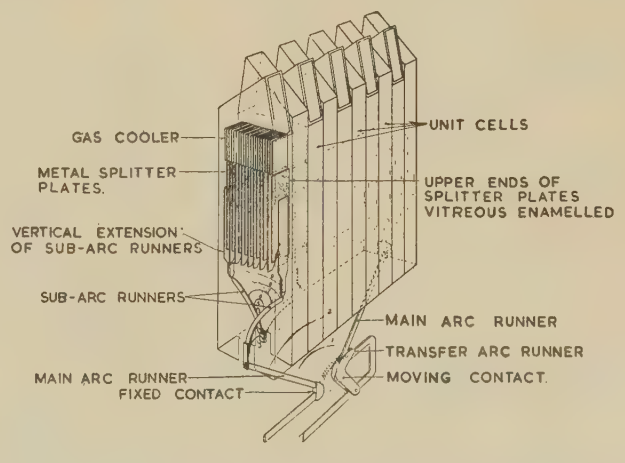


Fig. 5.—11 kV air-break arc chute of E.R.A. design. (The numbers show successive positions of the arc during interruption.)

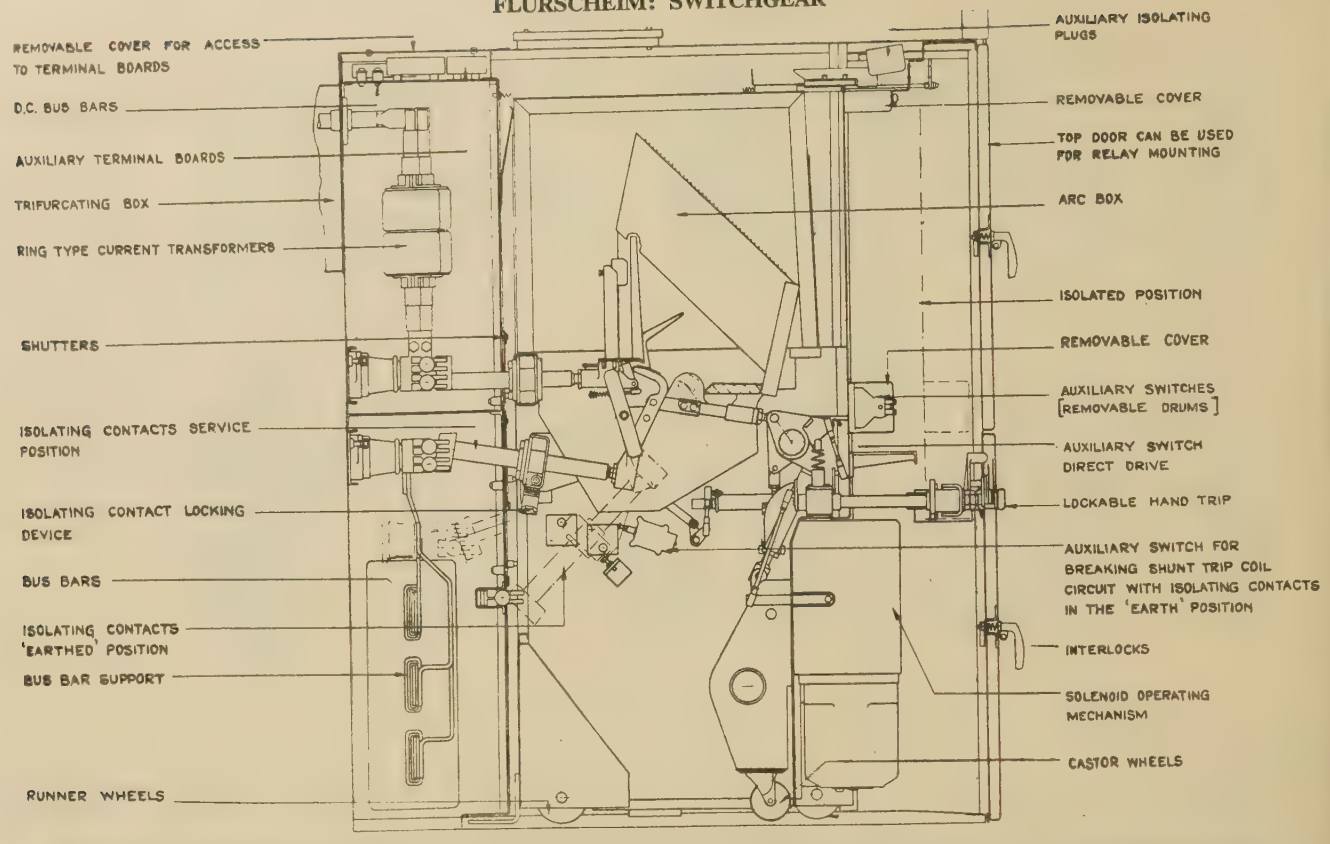


Fig. 6.—Air-insulated 3 kV metalclad unit with horizontal draw-out air-break circuit-breaker with rocking-bushing selection of busbar and earthing.

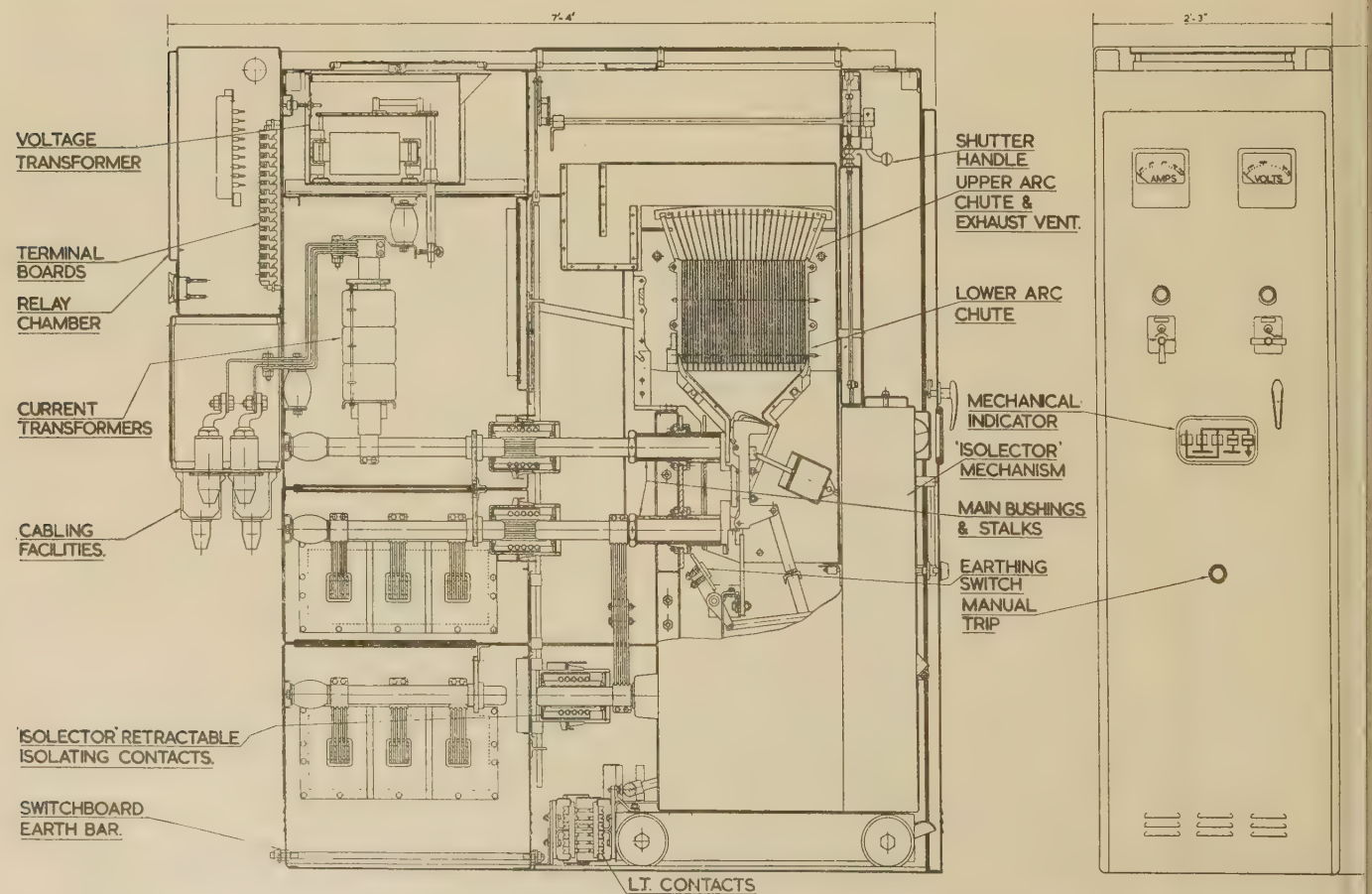


Fig. 7.—Air-insulated 3 kV metalclad unit with horizontal draw-out air circuit-breaker with plug selection of busbar and earthing.

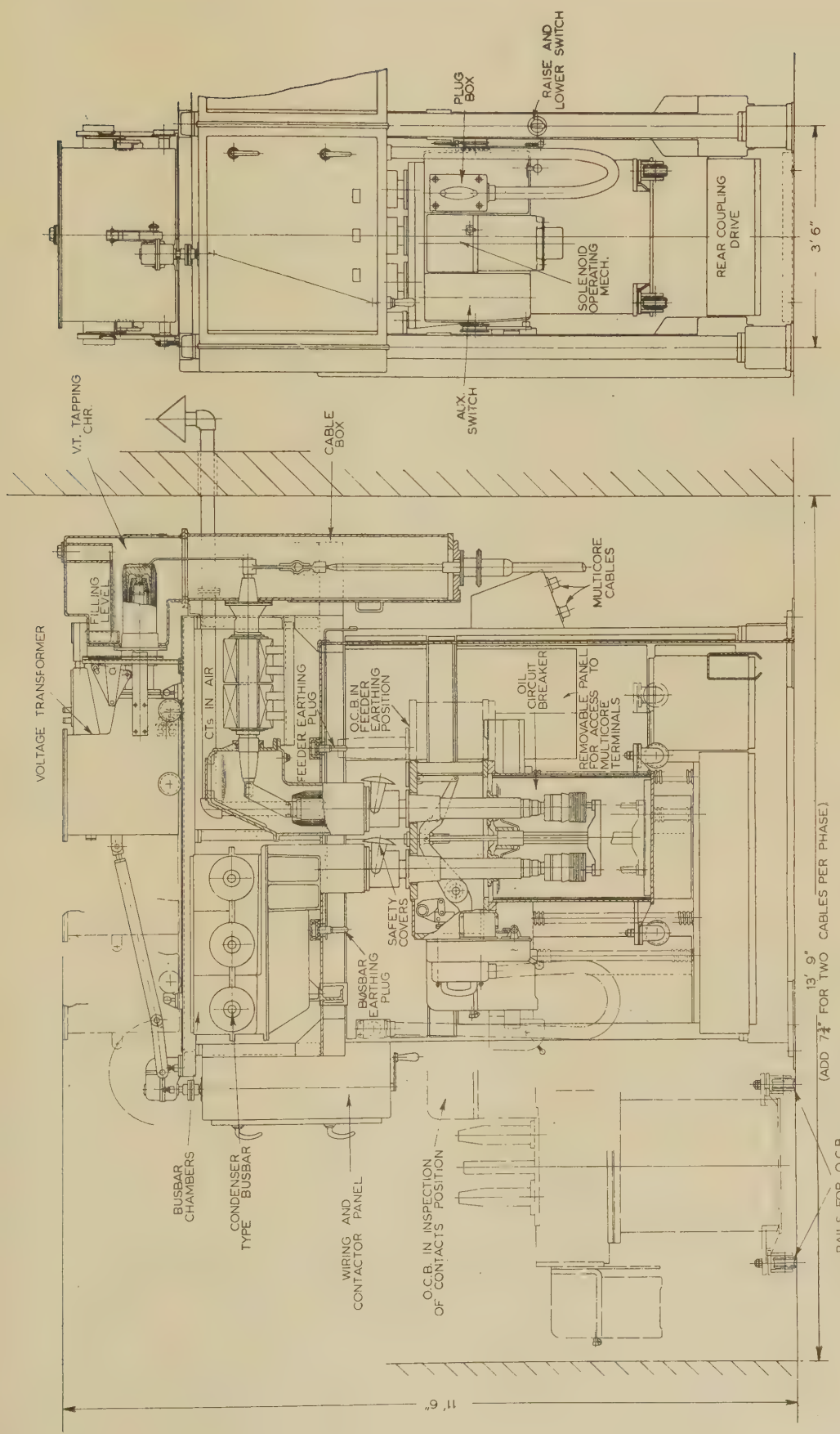


Fig. 8.—Vertical drop-down 33 kV 1 000 MVA metalclad unit with condenser-bushing busbars and electro-mechanical lift gear.

and 3·3 kV 250 MVA gear is now available. This type of circuit-breaker employs asbestos-base or ceramic arc chutes and operates by increasing the arc resistance within the chute by extending the length of arc, and by cooling with the aid of metal fins or similar devices. The introduction of resistance by means of the arc itself modifies the power factor of the circuit, and reduces the voltage severity in terms of instantaneous restriking-voltage rate and peak, thereby reducing the dielectric duty at final interruption. One of the major problems arising is therefore the disposal of the considerable energy released during the power-factor correction period; this energy is dissipated by hot ionized gases, which, if not properly controlled, can lead to flashover within the metalclad enclosure. Design attention has been concentrated on the reduction of this energy release by reduction of arc duration, and on effective disposal measures for these gases.

An arc chute of interest (see Fig. 5) has been developed by the E.R.A. for voltages of 6·6 and 11 kV. It has a multi-cellular arrangement of the arc-chute components; and the conductors are so disposed as to assist in forcing the arc up each separate component of the chute.

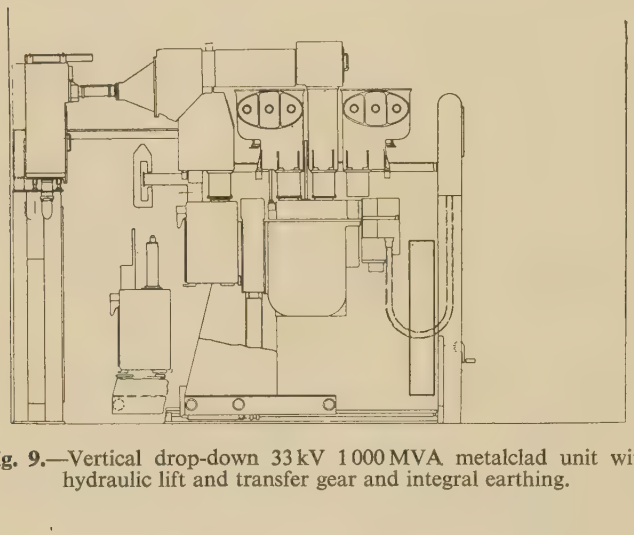


Fig. 9.—Vertical drop-down 33 kV 1 000 MVA metalclad unit with hydraulic lift and transfer gear and integral earthing.

(3.2.3) **Metalclad Enclosures.**

Although both horizontal and vertical isolation are employed in metalclad equipments, the general trend is towards horizontal isolation for air-insulated gear and vertical isolation for oil circuit-breakers. At 440 volts, air-break gear is usually arranged in multi-tier form, but at higher voltages, single-tier construction is usual on account of dimensional requirements.

Air-break designs lend themselves to simple methods of bus-bar selection and earthing, the trend being towards built-in selection and earthing systems, as opposed to removable plugs and separate portable earthing devices. Fig. 7 shows a design of 3·3 kV air-break unit arranged to give integral earthing and busbar selection by sliding plug contacts horizontally in and out to effect the desired changes of connections; this is done by means of a mechanism operated from the front of the unit. In the design shown in Fig. 6, the bushings are rocked to one of three alternative positions, two of which give busbar selection and the third earthing.

With oil circuit-breakers, the class of construction described above is not practicable, and with vertical drop-down units, transfer busbar change-over has become virtually standard, the circuit-breaker being isolated by vertical movement and moved from one busbar to another by horizontal traversing. These units, at the lower voltages, are truck-mounted with manual lifting gear. Fig. 1 is typical of 11 kV 500 MVA vertical drop-down construction, in which a flush-fronted appearance is obtained by means of doors giving access to instrument and circuit-breaker compartments. Fig. 2 is typical of designs in which direct access is afforded to the circuit-breaker truck, with the mechanism visible on the front panel.

Figs. 8 and 9 are typical of 33 kV 1 000 MVA drop-down designs. At these voltages, lifting is usually done by electro-mechanical means. The circuit-breaker of Fig. 9 is electro-hydraulically operated for both vertical isolation and horizontal transfer movement. This design also provides built-in earthing

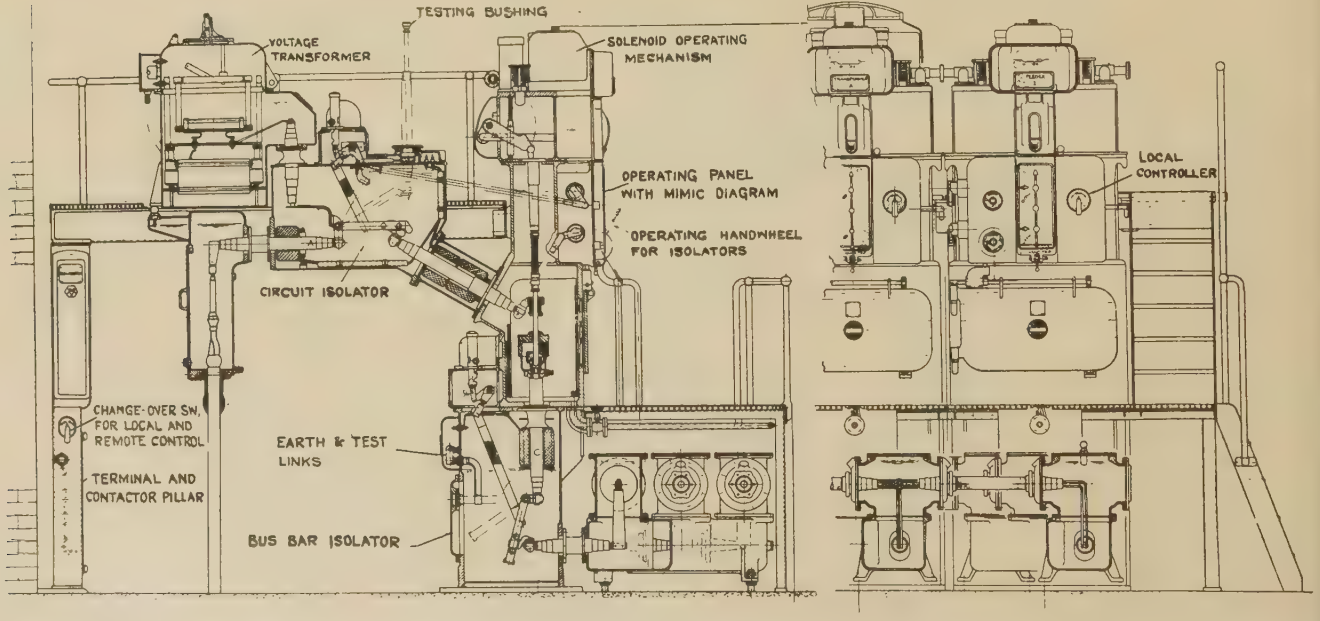


Fig. 10.—33 kV 1 000 MVA metalclad unit with fixed oil circuit-breaker, condenser-bushing busbars and oil-immersed selection of busbars and earthing.

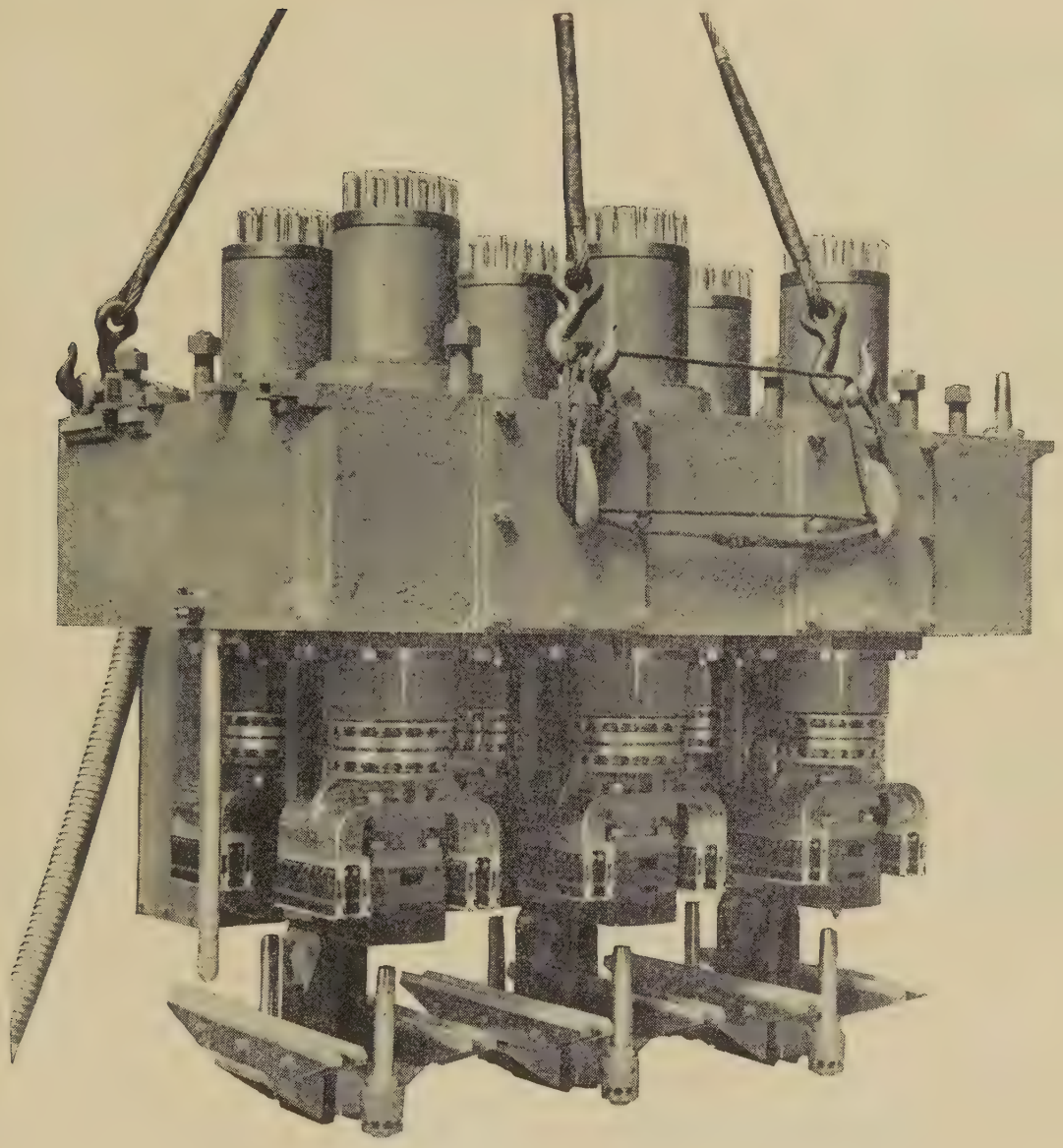


Fig. 11.—11 kV 4 000 amp 1 000 MVA oil circuit-breaker for use with vertical drop-down metalclad gear.

through the circuit-breaker by additional transfer positions, so arranged that the circuit-breaker can be lifted to positions which connect either busbar or feeder to earth.

An exception to the oil-immersed vertical-drop-down class is the fixed circuit-breaker equipment (see Fig. 10), in which isolation, earthing and busbar selection are carried out by oil-immersed isolators. This design was available before the war at 66 kV, but it has now been extended downwards for 33 kV power-station and substation service. This arrangement permits all insulation to be arranged permanently under oil and facilitates the mounting of busbars in separate fireproof compartments.

Metalclad boards have been developed for heavy-current duty; an 11 kV 4 000 amp metalclad circuit-breaker for 1 000 MVA is shown in Fig. 11. A design feature is the use of multiple plugs in parallel for isolation and multiple connectors for busbar joints.

All metalclad types are fully interlocked. The trend in design is towards a positive mechanism arranged so as to prevent the carrying out of an incorrect operation. Such an interlock is preferable to the type, common in the past, in which the circuit-breaker is tripped if an incorrect operation is attempted, and in which there is a risk of the interlock failing if the circuit-breaker contacts have been welded in the closed position.

Busbar insulation is usually by air, compound or oil, but at 33 kV, condenser-bushing bars have increased in use, and these are shown in Figs. 8 and 10. Both phase-segregated and non-phase-segregated types are available, but the differences are becoming smaller, and the same basic equipments can now often be built up in either form.

In all designs, more especially at the higher voltages, considerable reductions in size of metalclad structure have been obtained, in association with the reduction already referred to in circuit-breaker dimensions. Fig. 12 shows a comparison of the space required by a typical modern 33 kV 1 000 MVA metalclad unit, with that needed by a 33 kV design in 1932 for the same rating (787 ft^3 compared with 3 564 ft^3).

Further development is more likely to increase the MVA rating obtainable from a given dimension than to reduce the minimum volume needed for a given voltage. Other trends in metalclad design include increased interchangeability of circuit-

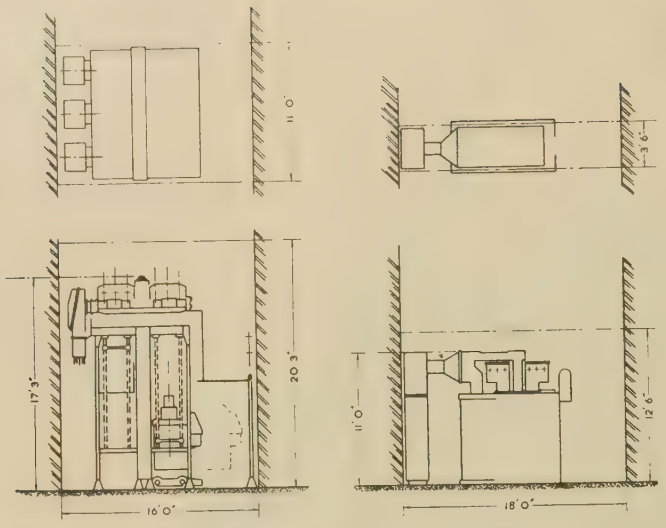


Fig. 12.—Comparison of space requirements for 1 000 MVA 33 kV metalclad equipment in 1932 and 1955 (3 564 ft³ compared with 787 ft³).

breakers of different current ratings within the same fixed structure by standardizing the plugging components. Independent operation of busbar and feeder spout shutters has also been introduced in order to facilitate cable and busbar testing. In all types, there has been a trend towards increased protection from dust, and towards improved appearance by using flush-mounting instruments and relays, or by enclosure of components.

(3.2.4) High-Voltage Indoor Construction with Open-Type Equipment.

Several high-voltage substations have recently been constructed employing outdoor open-type equipment arranged inside a building. These have been designed to give normal outdoor section clearances required for safety, but the volume of building has been reduced by the use of screens, or walls with through-wall bushings.

Fig. 13 is typical of such indoor high-voltage cubicle construction employing low-oil or air-blast circuit-breakers, but in which safety clearances and building can be reduced to a minimum by the use of swinging-bushing isolators and subdivision of the building into compartments. The station shown is of the double-busbar type, one set of busbars being accommodated in a central ground-floor chamber, and the other in a similar chamber above. From the circuit-breaker chambers, which are arranged back-to-back, cabling isolators (or bare connections on generator circuits) communicate with cable chambers on the ground floor, where cable sealing ends and voltage transformers also are accommodated.

A feature of this class of design is that it affords complete segregation of equipment, thus permitting safe maintenance and localizing damage in case of breakdown. The design is made possible by the use of a special isolator, in which a swivelled bushing passes through the wall or floor so that the aperture is sealed in any position of the isolator. In the open position, the bushing engages an earthed clip.

(4) OUTDOOR CIRCUIT-BREAKERS

(4.1) Foreign Practice

On the continent of Europe, the dead-tank oil circuit-breaker is in limited production at the lower voltages, but is virtually obsolete above 33 kV. Practice is divided between low-oil and air-blast designs at all voltages up to 380 kV.

All the low-oil circuit-breakers are now constructed without the automatic sequence switches at one time thought necessary

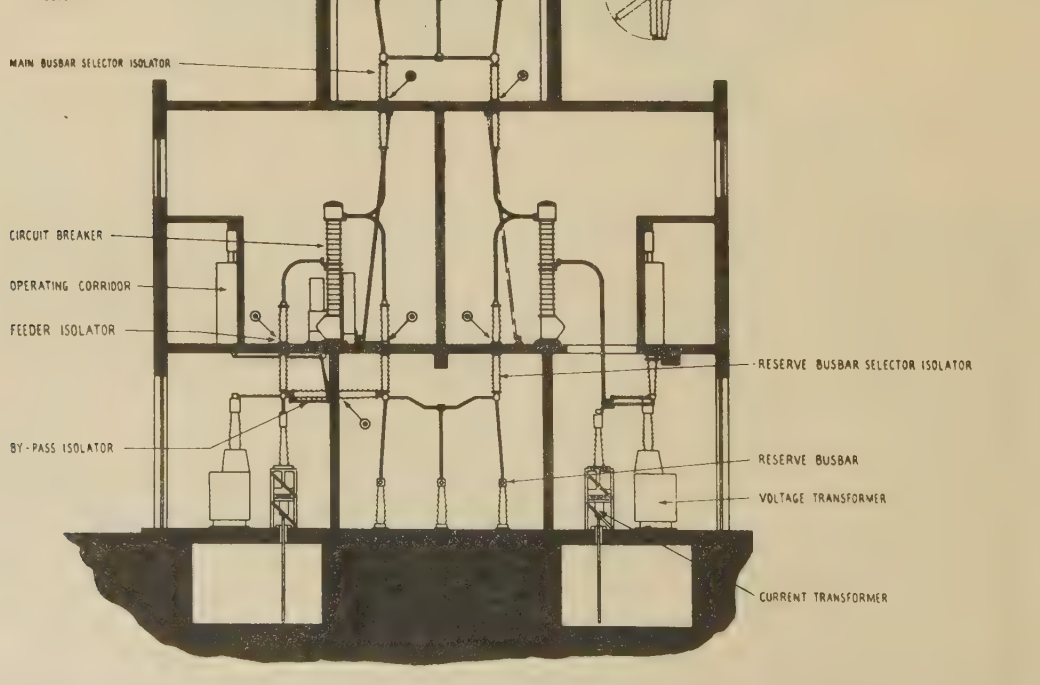


Fig. 13.—132 kV indoor station equipped with low-oil circuit-breakers and swinging-bushing isolators.

for dielectric security in the open position, and the majority of such designs are arranged with one vertical break in a tubular assembly, or with two such units arranged electrically in series for the higher voltages, reliance being placed on capacitance voltage division between the two units. Single breaks per pole are virtually standard up to 110 kV and, in some cases, even 220 kV, making possible twin-break constructions for 380 kV.

An exception is a design in which two interrupting components are mounted on a single column, one interrupter being solidly shunted by a low non-reactive linear resistance, and the second performing the final interruption and isolation function. This unit is rated up to 220 kV, two such assemblies being employed back-to-back for higher voltages.

In the design of air-blast circuit-breakers, there is a tendency to avoid forms of construction in which the interrupters are mounted one above the other; the general trend now is to mount the interrupting units in a horizontal array, thus making possible a symmetrical layout of the air supply to each unit. The rated voltage per unit in modern designs varies between 30 and 55 kV per break, as compared with an earlier maximum of 110 kV. Voltage distribution across multi-break designs is normally controlled by capacitance or high resistance of linear or non-linear form, or by both in parallel.

While a standard form of interrupter arrangement is emerging, widely different means are employed for isolation. In one design, the interrupting nozzles are held open under continuous air pressure, thus dispensing with any form of external isolation. Another design uses a multi-break isolating unit in series with the interrupting units, the isolation unit being enclosed and subjected to moderate air-blast during interruption. A third type employs a moving contact with part of its travel in open air, serving a dual function of isolation and interruption. A fourth class of construction uses a separate open air-break isolating switch. Yet a further design is being developed in which the interrupting elements are suspended from the sub-station structure; and remotely-mounted circuit-isolating switches, required for maintenance, are used with automatic sequence control as components of the circuit-breaker, thus rendering unnecessary any built-in isolation in the circuit-breaker itself.

These low-oil and air-blast designs are available for short-circuit ratings of the order of 10 000–15 000 amp and MVA levels of the order of 5 000–8 000 MVA (symmetrical).

In America, air-blast circuit-breakers, principally of European origin, have been applied in a number of networks, more especially in Canada; circuit-breakers designed in America are mostly of the dead-tank oil circuit-breaker class. These dead-tank circuit-breakers have been developed to provide 3-cycle performance and breaking capacities up to 40 000 amp total current; they use compressed-air closing mechanisms in the majority of designs, but, in some cases, stored hydraulic energy is utilized. The interrupters of all types have a common denominator in cross-blast action, and this is aided, with difference in degree, by limited force-blast oil flow provided by stored spring energy; this aid is needed more especially for the interruption of capacitive currents. Some form of high pure-resistive voltage grading is usually employed at the higher voltages; earlier low-value linear-resistance designs appear to be superseded by these new developments.

American low-oil circuit-breakers are represented by a multi-break horizontal arrangement using forced oil blast for interruption and capacitance grading across the multi-breaks. One Canadian 132 kV air-blast circuit-breaker is of the dead-tank type, with the interrupters enclosed within the high-pressure air receiver. Conventional bushings are used for bushing current transformers, and compressed air is the dielectric for insulation to earth and isolation.

(4.2) British Practice

Development in the outdoor circuit-breaker field is, perhaps, more marked than in any other, for the performance required from these circuit-breakers has increased at an unprecedented rate, more especially as regards fault power to be controlled. Whereas in Britain, in 1939, a 1 500 MVA rating was standard at 132 kV and the maximum rating was 2 000 MVA, the present requirements are for 3 500 MVA at 132 kV and 7 500 MVA at 275 kV, based on symmetrical current. Higher ratings will be required in England in the not-too-distant future, and British designs are already available for r.m.s. total interrupting currents of 40 000 amp up to 300 kV service rating. In the same period the general level of total break time has been halved.

No uniform trend is apparent in British practice, as dead-tank, low-oil and air-blast units are built throughout almost the whole voltage and MVA range.

Features of design which have received especial attention in British development are the ability to prove short-circuit ratings and effective over-voltage control. The pressure for more exhaustive proof of ratings has led, not only to the construction of larger short-circuit test plants, but also to multi-break designs which, as one feature of their conception, permit of full-scale testing of component interrupters with the appropriate current and voltage corresponding to maximum service duty. The attention devoted to over-voltage control and voltage distribution has led to the increased use of resistance or capacitance shunting, and to extensive testing with a view to eliminating excessive voltages produced by current chopping.

A further aspect of design, which has led to differences in construction between British and foreign circuit-breakers, is the consideration given to rate of rise of restriking voltage. The solid nature of the British Grid networks has shown the possibility of restriking rates much higher than those envisaged in Continental specifications, and the rates for which British circuit-breakers have been designed are, in many cases, correspondingly high.

Fig. 14, curve (*a*), shows the general trend of r.r.r.v. proposed

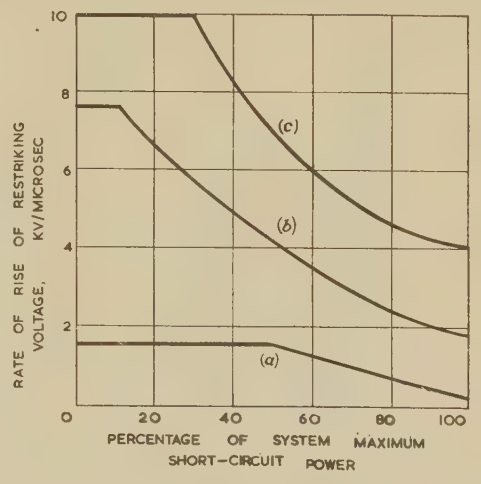


Fig. 14.—Rates of rise of restriking voltage for 220/275 kV systems.

(*a*) Proposed Continental values for 220 kV [Juillard, E., and Kukth: C.I.G.R.É. (Paris), 1950, Paper No. 147].
(*b*) Calculated values for British 275 kV Grid system [Gosland, L., and Vosper, J. S.: C.I.G.R.É. (Paris), 1954, Paper No. 135].
(*c*) Specified values for circuit-breakers for British 275 kV Grid system.

on the Continent for 220 kV; curve (*b*) shows the envelope of extreme values of r.r.r.v. calculated for the British 275 kV network; curve (*c*) shows the r.r.r.v. for which British 275 kV 7 500 MVA circuit-breakers have been designed. The following

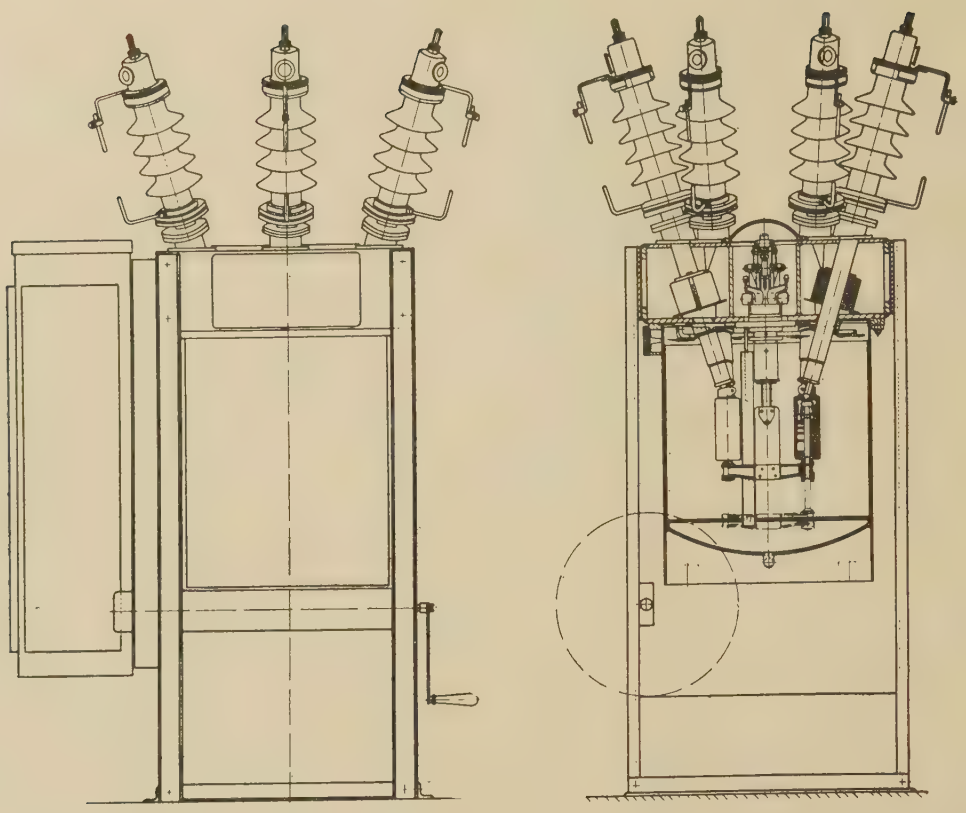


Fig. 15.—Single-tank 33 kV 1 000 MVA outdoor circuit-breaker arranged for shipment fully assembled.

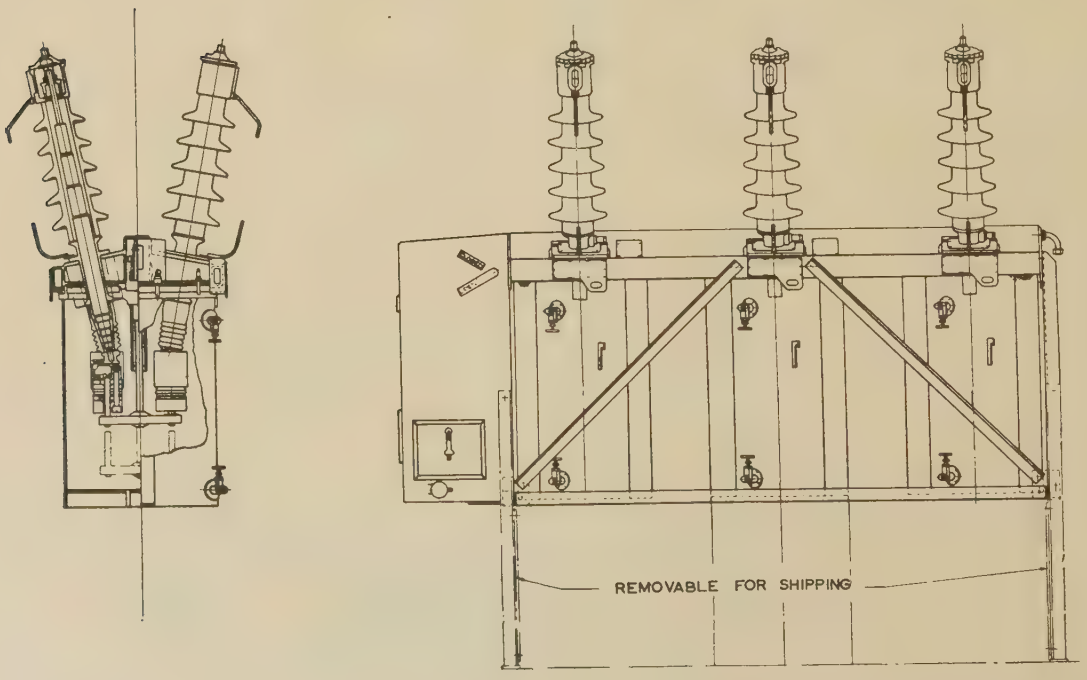


Fig. 16.—Three-tank 66 kV 1 500 MVA outdoor circuit-breaker arranged for shipment fully assembled.

r.r.r.v.'s at the given percentages of rated breaking capacity have been proposed as a British standard for 220/275 kV: 7 kV/microsec at 30%; 2·5 kV/microsec at 60%; 1·5 kV/microsec at 100%.

(4.2.1) **Dead-Tank Oil Circuit-Breakers.**

At 33 and 66 kV, dead-tank oil circuit-breakers are usually of conventional double-break construction, although some single-break units are available. The trend of design is towards a single-tank circuit-breaker for ratings up to 1 000 MVA, with three-tank circuit-breakers above this level, but at both voltages some designs are available with three-tank construction throughout the MVA range.

Design improvements have resulted in an increased MVA rating per ton of circuit-breaker, with shorter total break times, which are now of the general order of 4–5 cycles, or half the pre-war level. These improvements have resulted also in a reduction of the work required on site during erection, and in modifications permitting shipment in one piece with all adjustments factory made. Fig. 15 is typical of the general arrangement of a single-tank 33 kV oil circuit-breaker with a 1 000 MVA rating and designed for one-piece shipment. Similar arrangements are in general use at 66 kV, but at this voltage the air clearances necessary for the bushings may make bushing removal necessary for shipment. Fig. 16 shows a typical 66 kV 750/1 500 MVA circuit-breaker in which one-piece shipment is possible, owing to the reduction in overall width associated with three-tank construction.

The closing mechanisms used with these and other higher-voltage oil circuit-breakers are normally of solenoid, stored-energy-spring or compressed-air type. Compressed-air closers are usually recharged by centralized compressor plants arranged to operate all circuit-breakers in a station; they have either mechanical trip-free linkages, or alternatively solid linkage with automatic dumping of the closing compressed air on completion of a closing duty. The former offers trip-free operation throughout the closing stroke, and requires resetting of the linkage for high-speed reclosing duty; the latter arrangement is free to trip when closed, and enables the piston to be coupled directly to the circuit-breaker coupling rods.

Fig. 17 shows schematically a stored-energy type of closing mechanism in which the storage medium is gas compressed to 4 000 lb/in^2, thus permitting the power for a number of closing operations to be made available from a relatively small storage

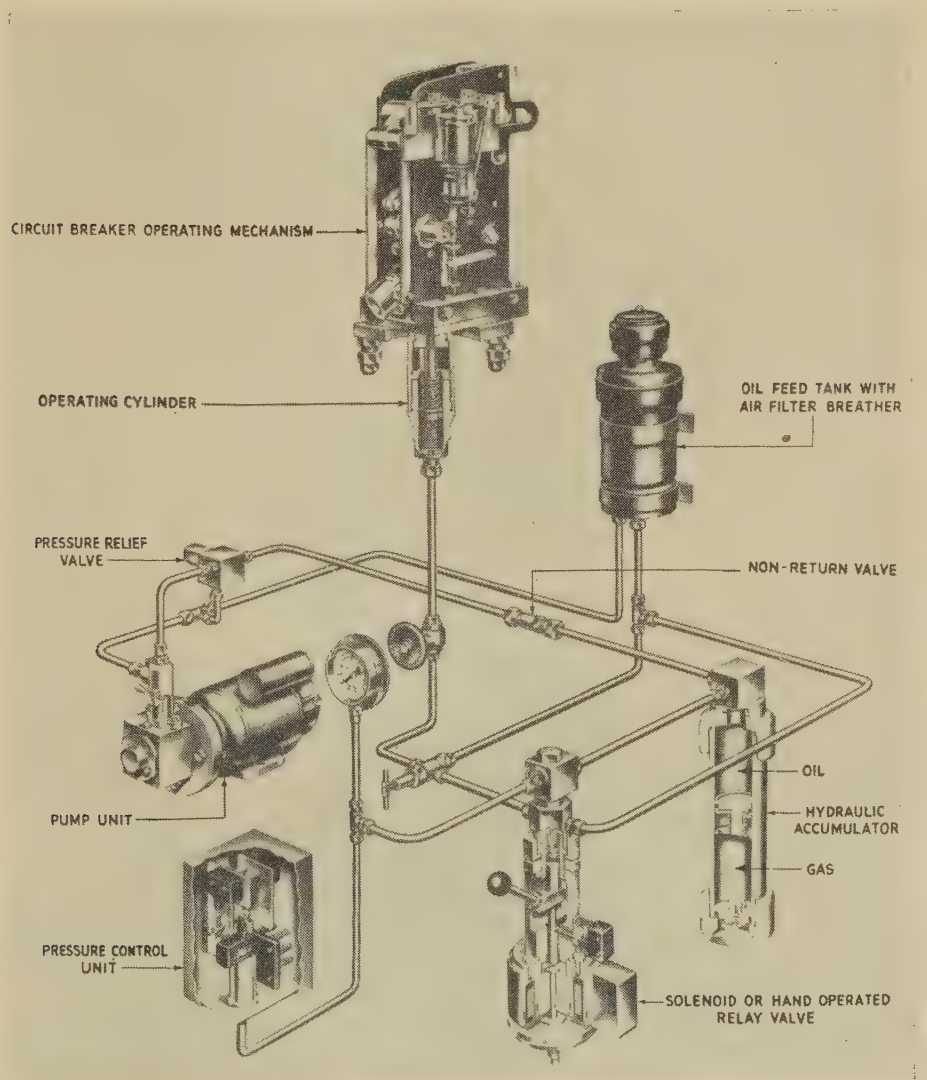


Fig. 17.—Hydraulic circuit-breaker closing mechanism with high-pressure air drive.

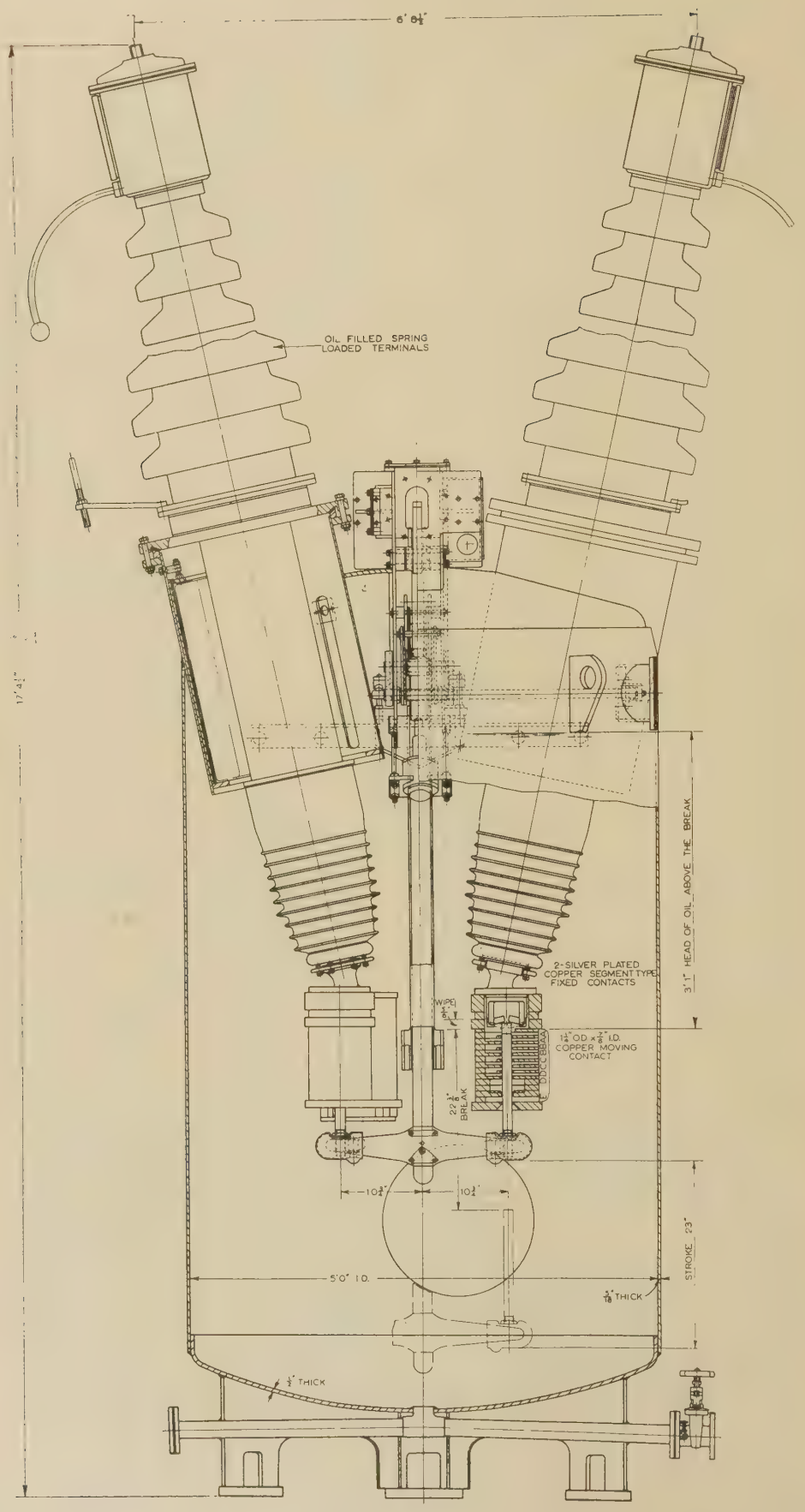


Fig. 18.—Single pole of three-tank oil circuit-breaker for 132 kV 3 500 MVA, with linear-resistance shunting.

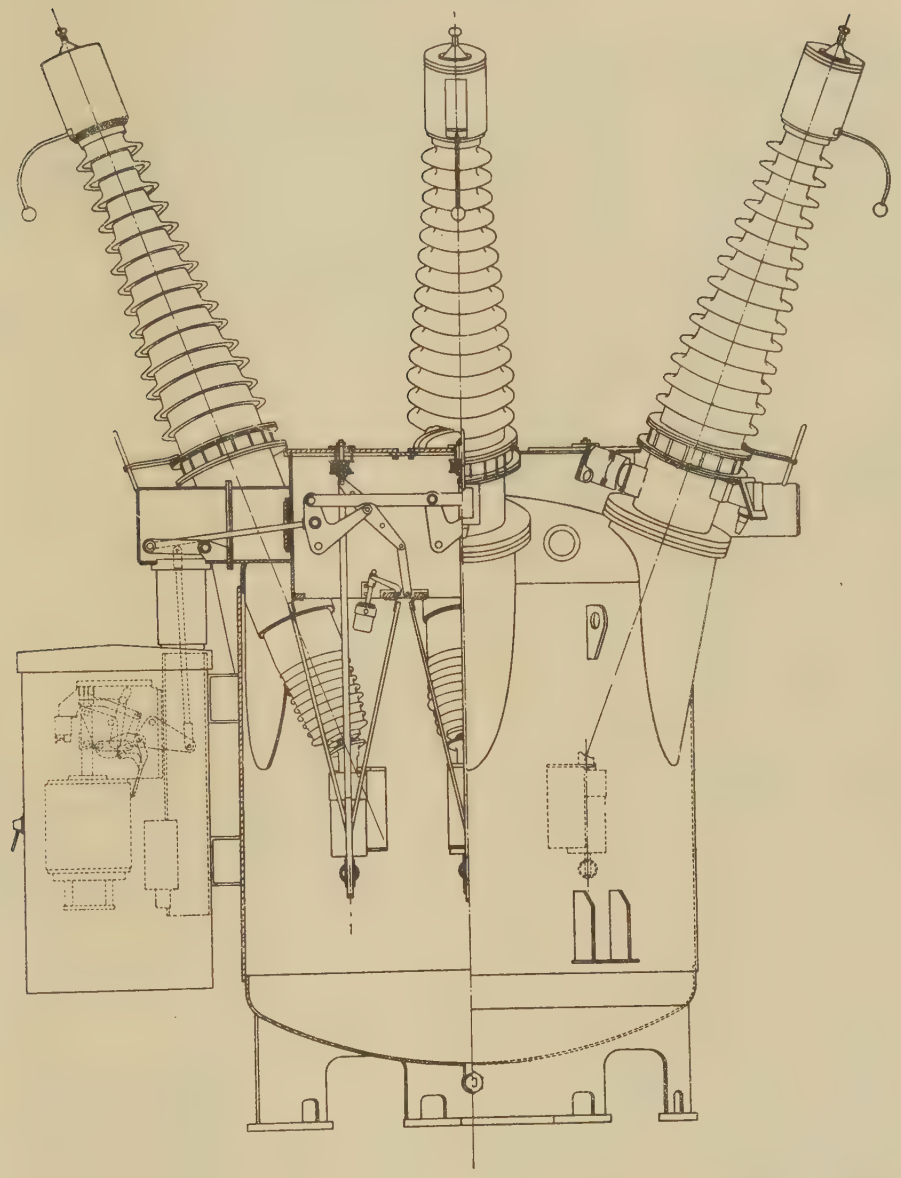
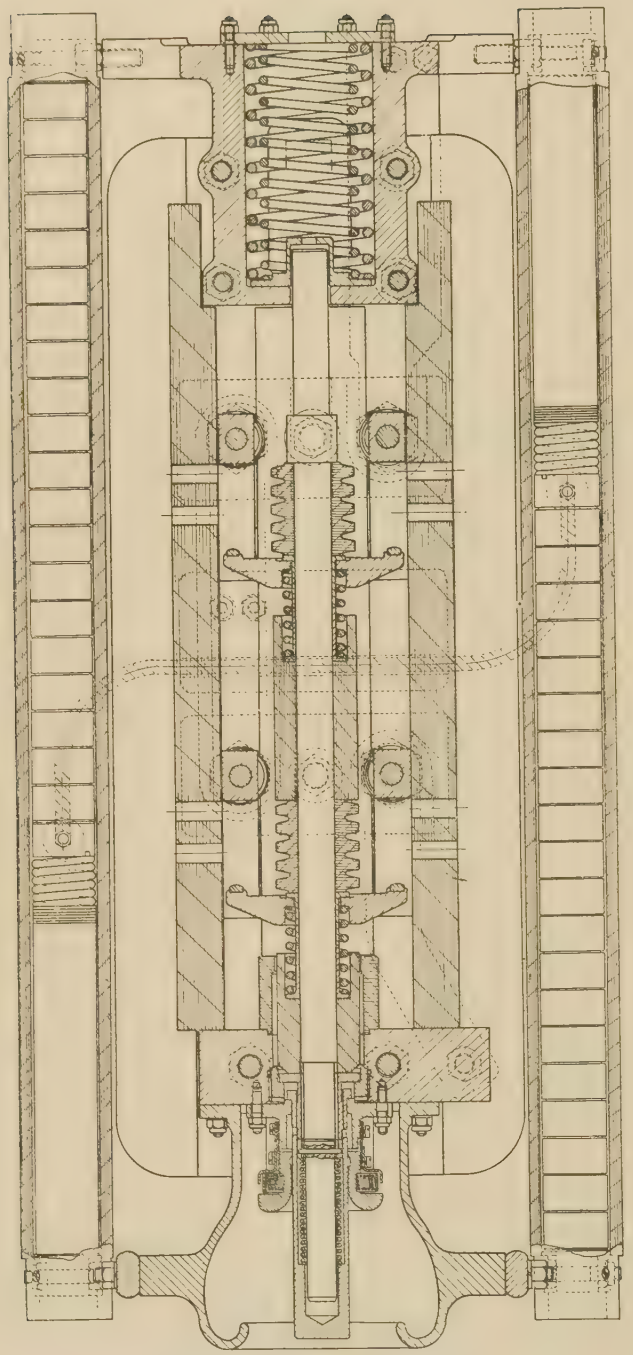


Fig. 19 —Single-tank 132 kV 2 500 MVA oil circuit-breaker, with linear-resistance shunting.

accumulator. The compressed gas drives the circuit-breaker-mechanism closing piston through the medium of an oil transmission system, the oil being separated from the gas by a seal, in the form of a floating piston within the storage accumulator. To close the circuit-breaker, a small valve is opened permitting flow of high-pressure oil. The accumulator is kept charged to working pressure by a small motor-driven pump and automatic pressure switch; the gas is permanently sealed and does not need replacement.

The MVA ratings available at the higher voltages have increased continuously and now include 2 500 MVA at 66 kV, and 3 500 MVA or 5 000 MVA at 132 kV, based on symmetrical current, with asymmetrical current ratings 25% higher. The higher-breaking-capacity designs are generally of 3-cycle total-break-time performance; the necessary high acceleration of moving contacts has been achieved by weight reduction, by powerful mechanisms, and in some cases by the use of torsion-bar springs.

Dead-tank oil circuit-breakers for 110–132 kV service are, principally, of double-break 3-tank construction for 2 500–3 500 MVA (see Fig. 18), but one single-tank design for 2 500 MVA at 132 kV is shown in Fig. 19. Linear-resistance shunts (see Figs. 18 and 19) are used in a number of designs to ensure good voltage grading. These are of the order of 3 000 ohms per pole and reduce the restriking voltage rate and peak, thereby reducing the restriking-voltage duty on the interrupters. At high natural frequencies, this damping can halve the transient voltage duty. These shunts also serve to discharge partially the energy trapped on long open-ended transmission lines when disconnected on no-load; they thus reduce the voltage build-up across the circuit-breaker during the first half-cycle of interruption, and therefore the amplitude of any restrike voltage that may occur should the arc gap break down in this period. The design is such that the resistive currents are themselves interrupted by a plain-break action later in the circuit-breaker stroke. The resistive current persists for about one or two cycles beyond main arc extinction, but it is too small to affect network stability.



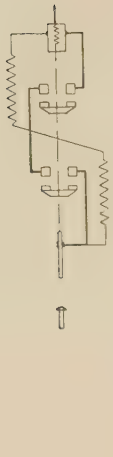


Fig. 20.—Four-break interrupter forming part of eight-break 132 kV 3 500 MVA oil circuit-breaker, with non-linear-resistance shunting.

An alternative approach, used in one design, is to employ two interrupters per pole, each containing four breaks (see Fig. 20), leading to a very rapid arc extension. In this design, 3-cycle performance and restrike-free capacitive-current interruption are retained with relatively low contact speeds. non-linear high-resistance shunts in which $I = kV^{4 \cdot 5}$ (approximately) are used for voltage-grading purposes. These shunts serve also the additional duty of damping any over-voltages produced by the circuit-breaker when disconnecting small inductive circuits, and can limit these to the order of twice the phase-to-neutral peak voltage.

A dead-tank design for 7 500 MVA at 275 kV is shown in Fig. 21; designs for ratings up to 15 000 MVA and up to 275 kV

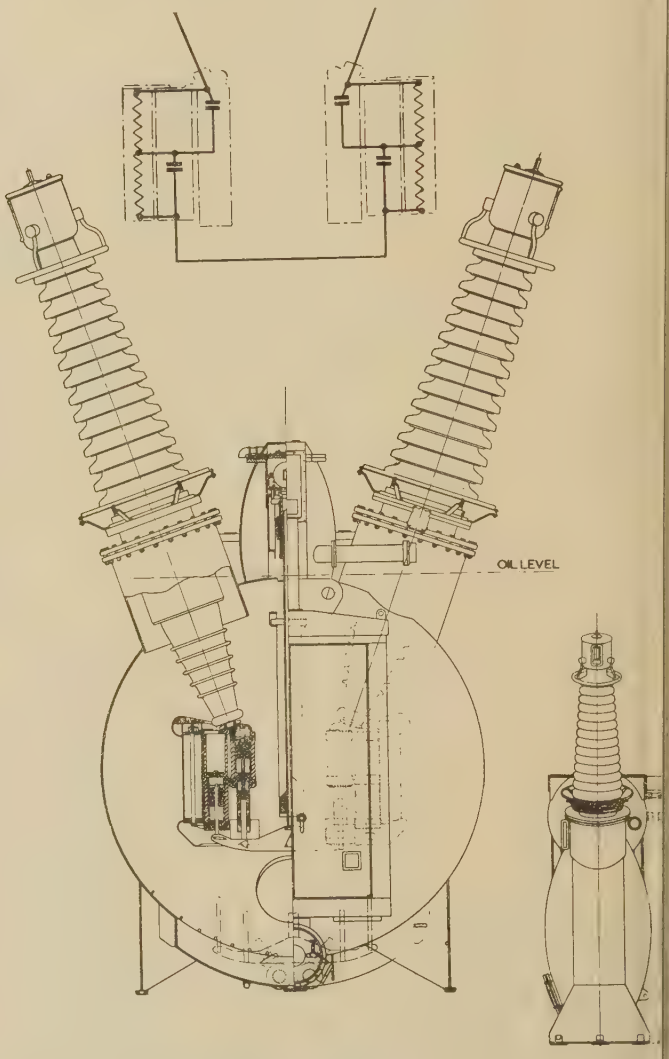


Fig. 21.—275 kV 7 500 MVA "watchcase"-tank oil circuit-breaker with four breaks per pole and linear-resistance shunting. Inset: schematic showing circuit connections.

are generally similar. This circuit-breaker, extending the principles used at 132 kV, employs four breaks in series per pole with linear-resistance shunts and gives a total break time of 0·06 sec. In order to economize oil, the tank has been formed in "watchcase" shape, giving a reduction in oil volume of the order of 33% as compared with conventional construction. Special means have been built into the circuit-breaker to aid rapid maintenance work, such as provision of oil pump, built-in air fan for gas removal, and built-in internal floodlighting.

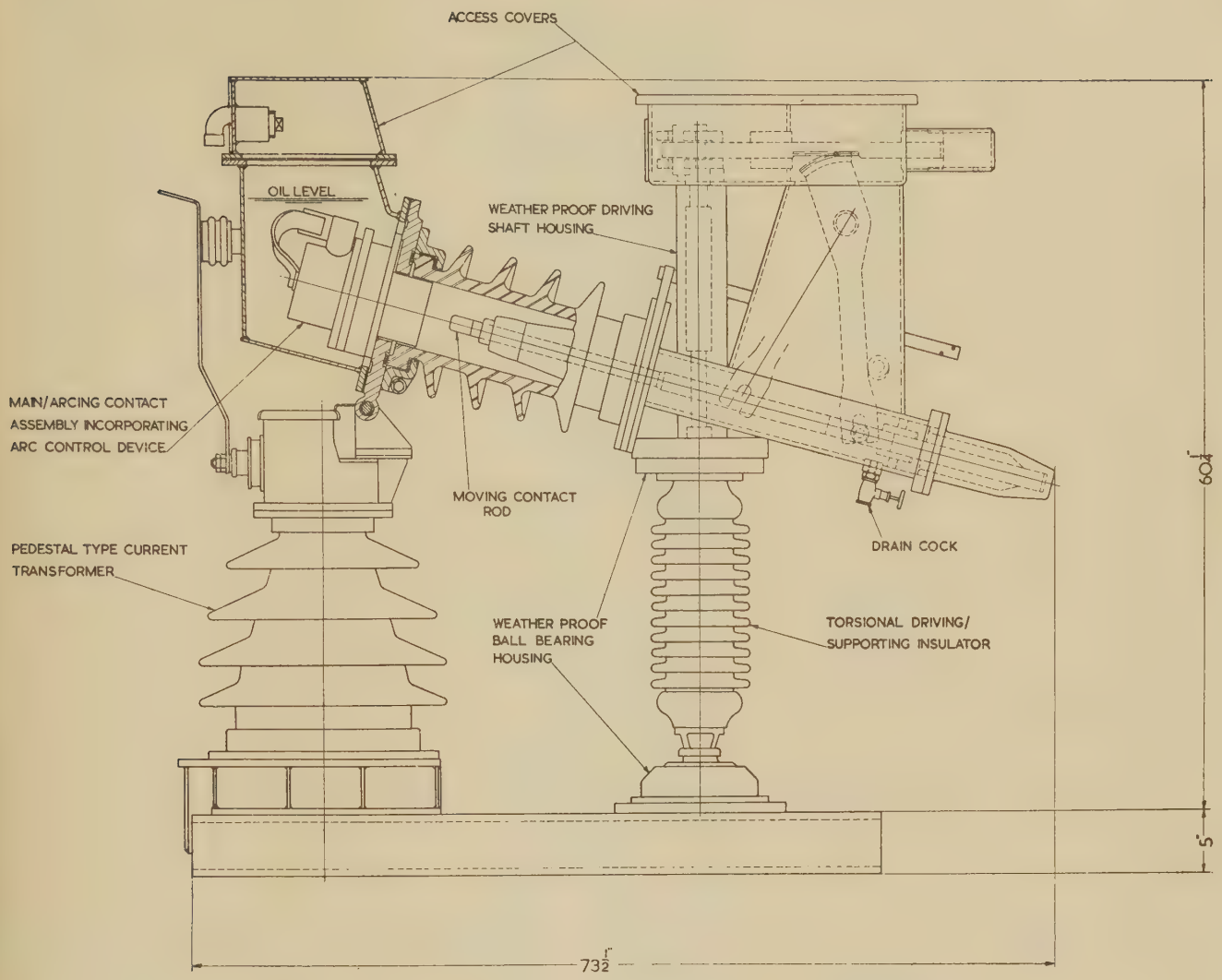


Fig. 22.—33 kV 750 MVA low-oil circuit-breaker with ceramic contact drive.

(4.2.2) **Live-Tank Low-Oil Circuit-Breakers.**

British designs of this type now dispense, as do Continental circuit-breakers, with the external series isolator formerly used, and interrupter assemblies are now, therefore, mounted vertically, or inclined, avoiding the risk of deposition of carbon possible with horizontal arrangements. The majority of these circuit-breakers use internal contact drives, which are oil immersed, and the dielectric security of the lower compartments is secured by segregation of the oil in the interrupting and supporting units. One 33 kV design (see Fig. 22), however, uses a ceramic drive, and employs the current transformer as a supporting element. The use of non-ceramic oil-immersed contact drives on the higher-voltage designs (see Figs. 23–24) has permitted high contact speeds and enables total break times of the order of 3–4½ cycles to be achieved at voltages of 66–220 kV.

Low-oil circuit-breakers are built with single breaks up to 132 kV (see Fig. 23), and with two units in series with capacitive voltage division for 220 kV (see Fig. 24). The grading capacitance dividers are built into the pressure tubes of the interrupting elements. Closing mechanisms are either compressed air or motor-wound spring. The use of high-speed contacts and efficient cross-blast interrupters has made possible ratings of 3 500 MVA at 132 kV and 5 000 MVA at 220 kV, to British Standards. With these designs, over-voltage, when disconnecting small reactive circuits, is controlled by suitably proportioning the interrupter components, and by using contact speeds so co-ordinated that the contact gap itself provides a natural safety gap.

(4.2.3) **Outdoor Air-Blast Circuit-Breakers.**

Outdoor air-blast circuit-breakers are in production for service at from 66 kV to 275/300 kV, and for all breaking duties so far required, i.e. to short-circuit currents of the order of 40 000 amp.

The general trend of design is towards multiple-break circuit-breakers with interrupting contacts held open only during the period of air blast. An automatic external sequential switch is used to provide isolation in open air after the contacts have reclosed. Two general arrangements of interrupter positioning are in use; in one the interrupters are mounted in a vertical column with, in most cases, a common air supply to the assembly (see Figs. 26, 27 and 28); one vertical design is arranged with independent air pipes to each interrupter. In the other arrangement the interrupters are disposed horizontally with symmetrical air-supply paths from the valve gear to each interrupter (see Figs. 25, 29 and 30); the air-flow paths are parallel and equal in length.

Interrupter design is, in general, of the single-flow axial-blast

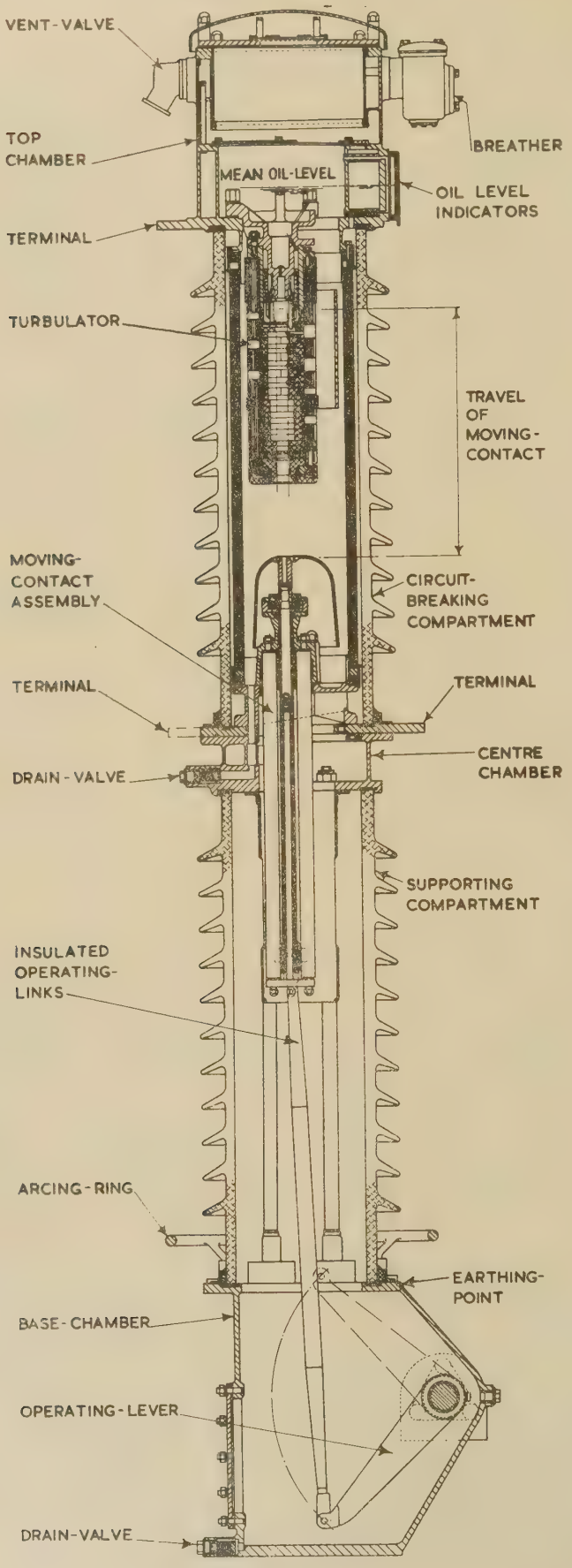


Fig. 23.—132 kV 2 500 MVA low-oil circuit-breaker with internal contact drive.

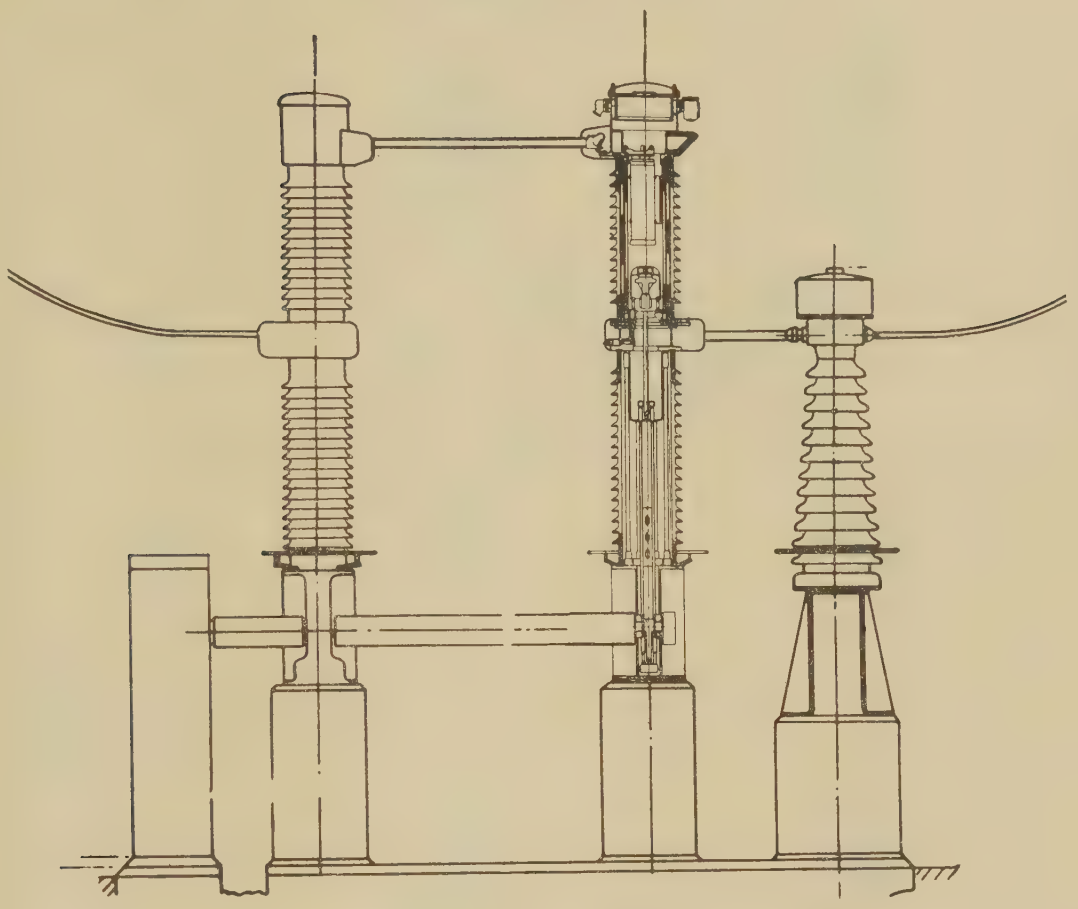


Fig. 24.—220 kV 5 000 MVA low-oil circuit-breaker.

type in which air is discharged in one direction through one opening for each break (see Figs. 28, 29 and 30). A double-flow double-exhaust design is used in one type.

Valve gear is usually mounted at earth potential on the air receivers. An exception (see Fig. 26) has both air receiver and valve gear mounted on the live component of the circuit-breaker, thus reducing the distance between valve gear and nozzle. In this case, remote operation of the blast valves is arranged from the chassis by means of ceramic compressed-air control pipes.

Sequence-switch construction has not been stabilized in any particular mechanical form, designs being available with rotation in either the vertical or horizontal plane. The motors for the sequence switches are arranged in some cases (see Fig. 28) at live potential with remote control, and in other cases (see Figs. 26, 27, 29 and 30) with the motor at earth potential driving the isolator through a porcelain column.

These air-blast circuit-breakers have a very short arc duration, of the order of 0·01–0·02 sec, and their mechanical trip times from receipt of trip impulse to contact separation are of the order of 0·03–0·05 sec, affording total break times of 0·05–0·07 sec. The high r.r.r.v. levels for which British air-blast circuit-breakers have been designed have already been referred to. As a consequence, these designs possess a high factor of safety in terms of the network performance required from them.

The general practice is to employ one interrupter for between 33 and 66 kV of the rated voltage, the tendency being towards 50 kV per break for short-circuit currents of 15 000 amp and of the order of 30 kV at 40 000 amp, as in Fig. 29.

Voltage division between breaks of multi-break designs is controlled by either non-linear resistance shunts as in Figs. 28 and 29, by linear resistance (Fig. 26) or by capacitance built into the interrupter assembly (Figs. 27, 30).

Facilities are provided for high-speed automatic reclosure duty, and two methods are employed. In the first the circuit-breaker and sequence switch are opened and closed sufficiently rapidly to ensure the required dead time of the order of 0·2 or 0·3 sec between de-energizing and re-energizing of the line. With this arrangement, powerful sequence-switch motors are necessary. In the second method, the interrupting nozzles alone are operated and the sequence-switch is left closed, which requires that the blast be maintained during the entire dead period in order to prevent nozzle reclosure. In this case, large air receivers are required to take care of the increased air consumption, and different tripping means are provided to select between a reclosing trip duty and a normal trip duty.

Over-voltage prevention during switching operations, as in the case of oil circuit-breakers, is provided in either of two ways. In one design (see Fig. 30), limitation of over-voltage due to current chopping is restricted by dielectric breakdown of the nozzles and appropriate control of dielectric characteristics. In other types (Figs. 28 and 29), the non-linear resistance elements used for voltage grading also serve to damp any over-voltages that may be produced from this source.

The use of relatively low voltage ratings per break, and of interrupters with short contact travel and high rate of build-up of dielectric strength, ensures that these circuit-breakers are virtually restrike-free when disconnecting long open-ended lines;

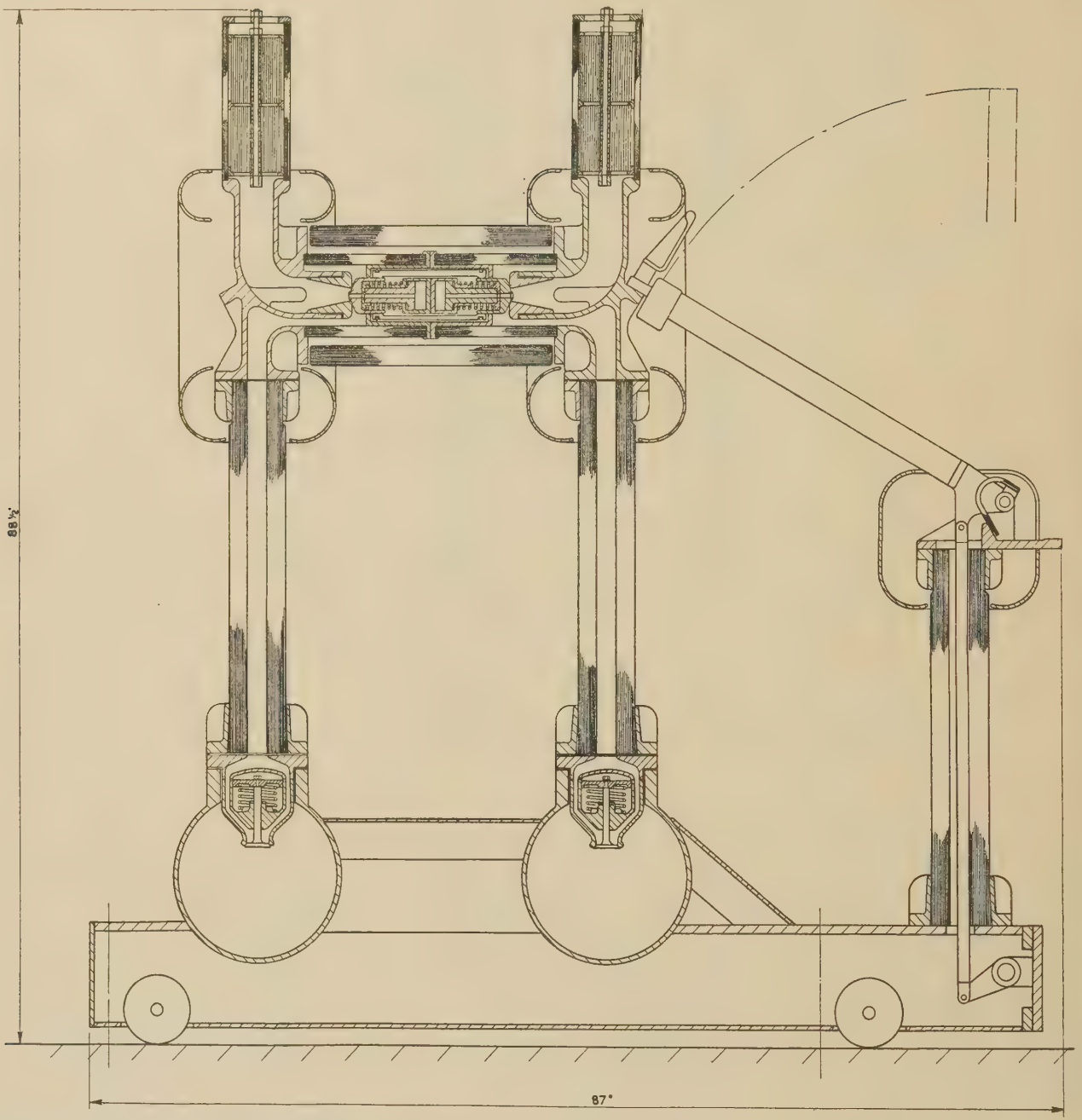


Fig. 25.—66 kV 2 500 MVA air-blast circuit-breaker for indoor cubicle or outdoor "blockhouse" mounting.

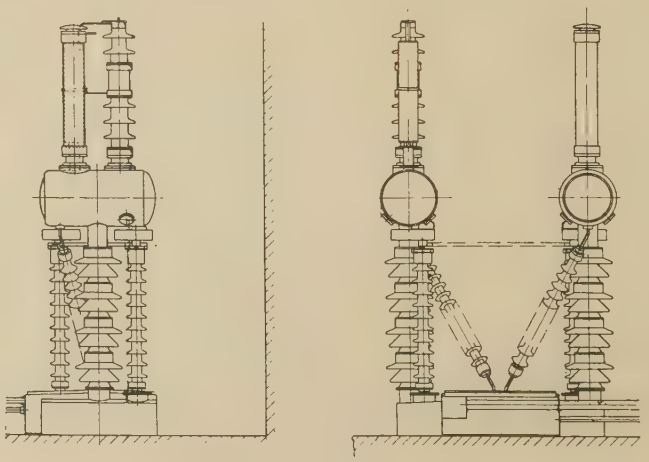


Fig. 26.—132 kV 2 500 MVA air-blast circuit-breaker arranged with live air receivers, linear-resistance shunting and sequence-switch motor in chassis.

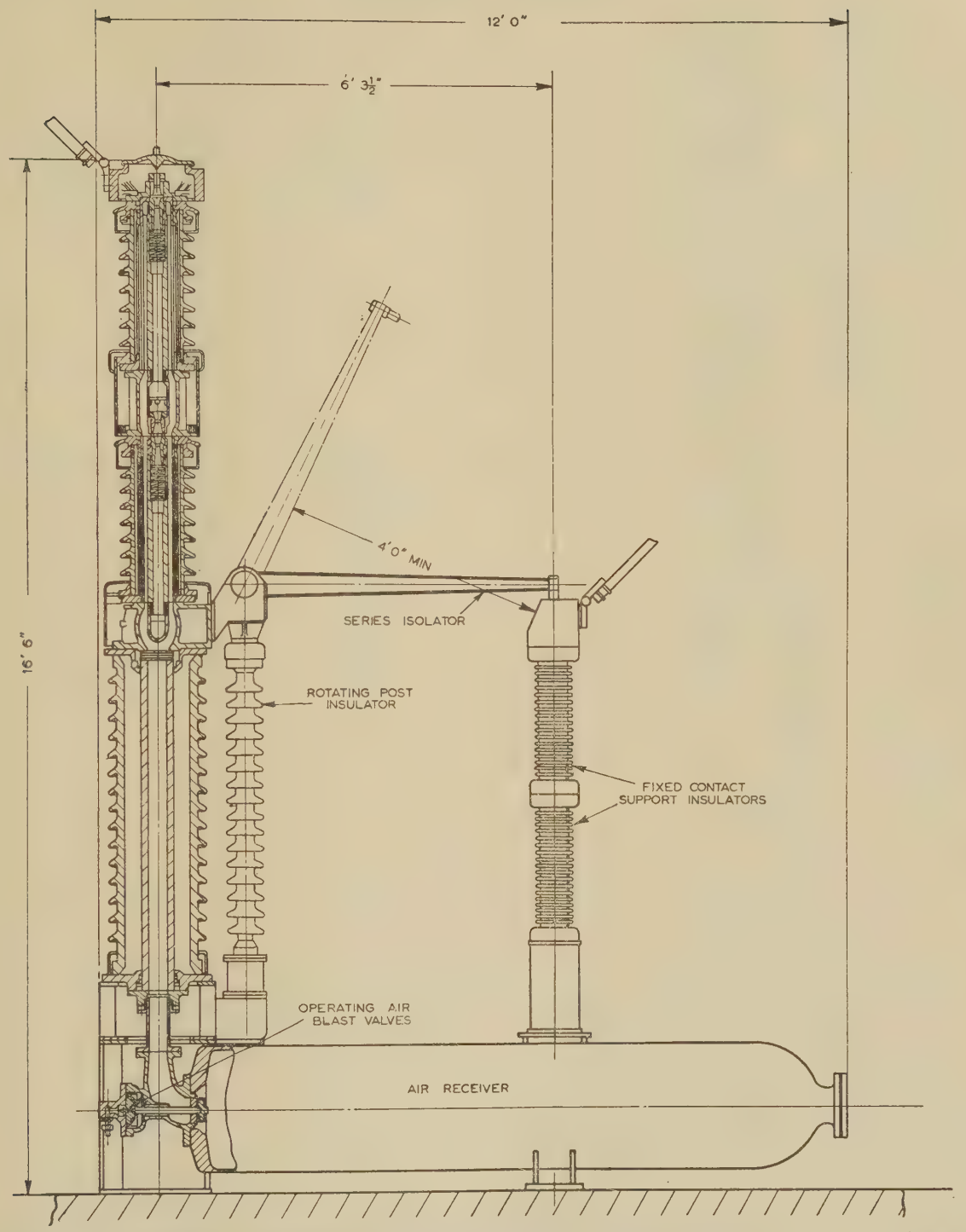


Fig. 27.—132 kV air-blast circuit-breaker with interrupters mounted vertically, with capacitance voltage grading and sequence-switch motor and air receiver at earth potential.

these designs are therefore free from over-voltage risks arising from capacitance switching duty.

(5) ACKNOWLEDGMENTS

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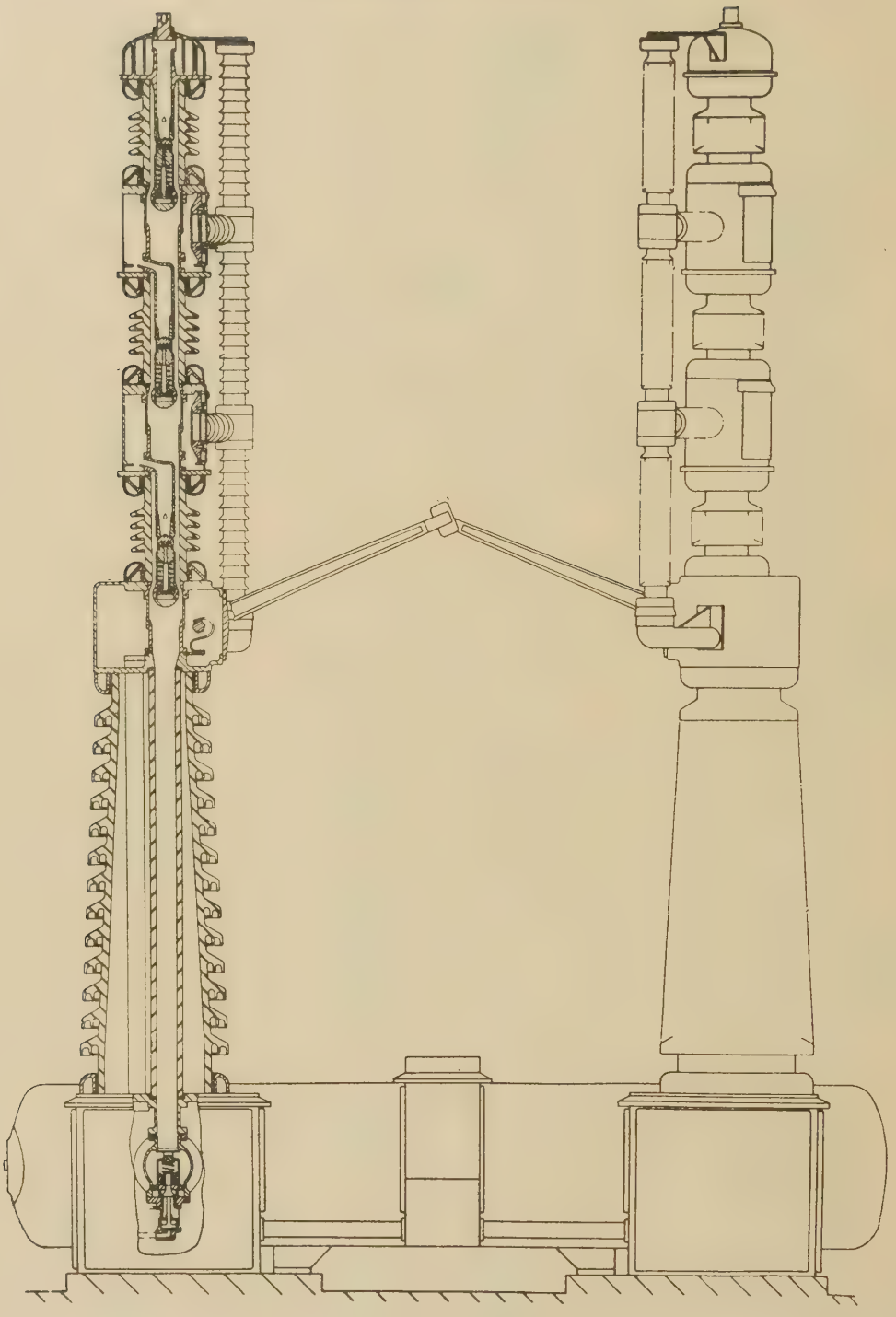


Fig. 28.—275 kV 7 500 MVA air-blast circuit-breaker with six breaks, arranged vertically, with non-linear-resistance grading and live motor for sequence-switch drive.

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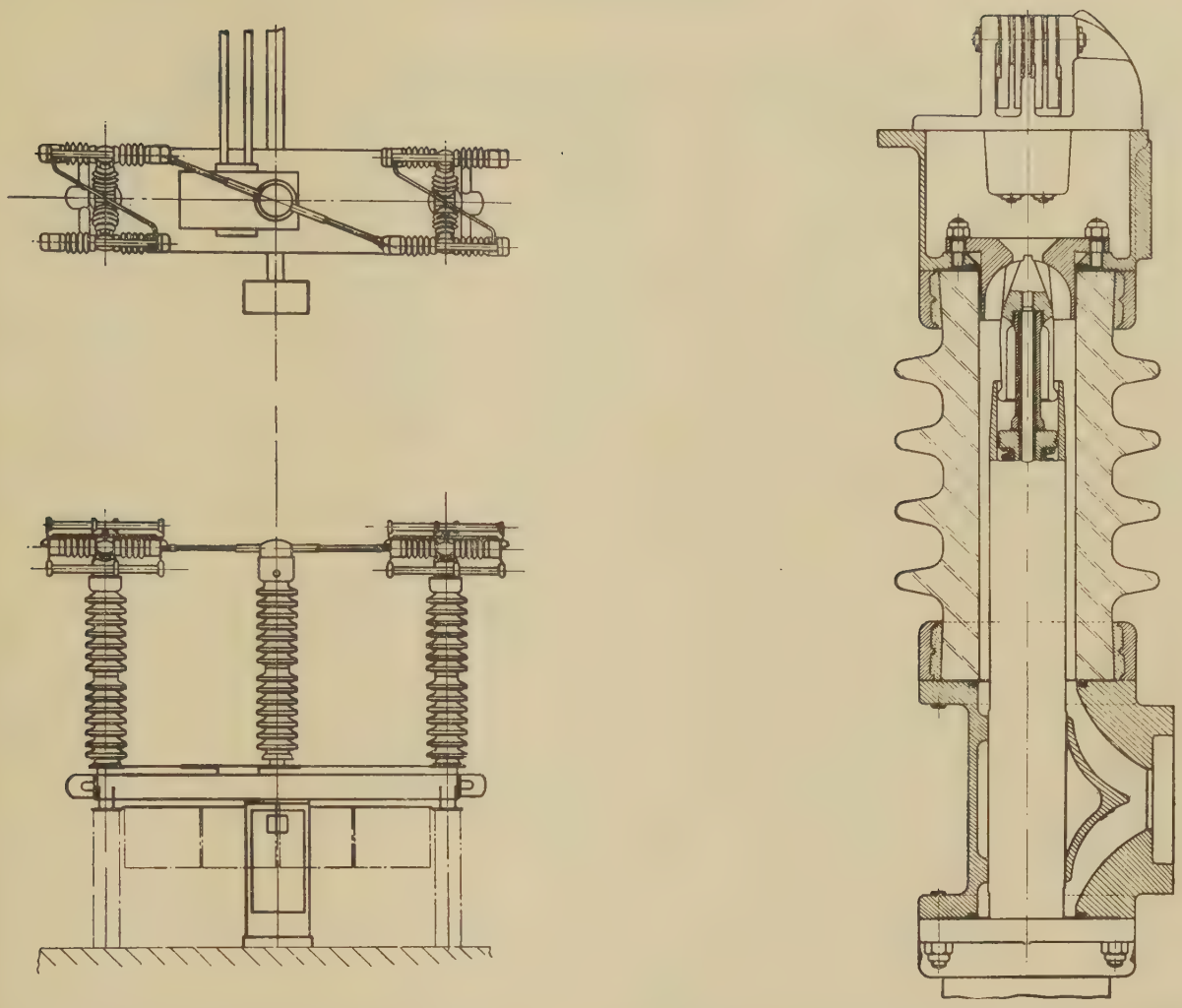


Fig. 29.—275 kV 7 500 MVA air-blast circuit-breaker with eight breaks horizontally arranged, with non-linear-resistance grading and sequence-switch motor mounted in chassis. On the right is shown the cross-section of a single interrupter.

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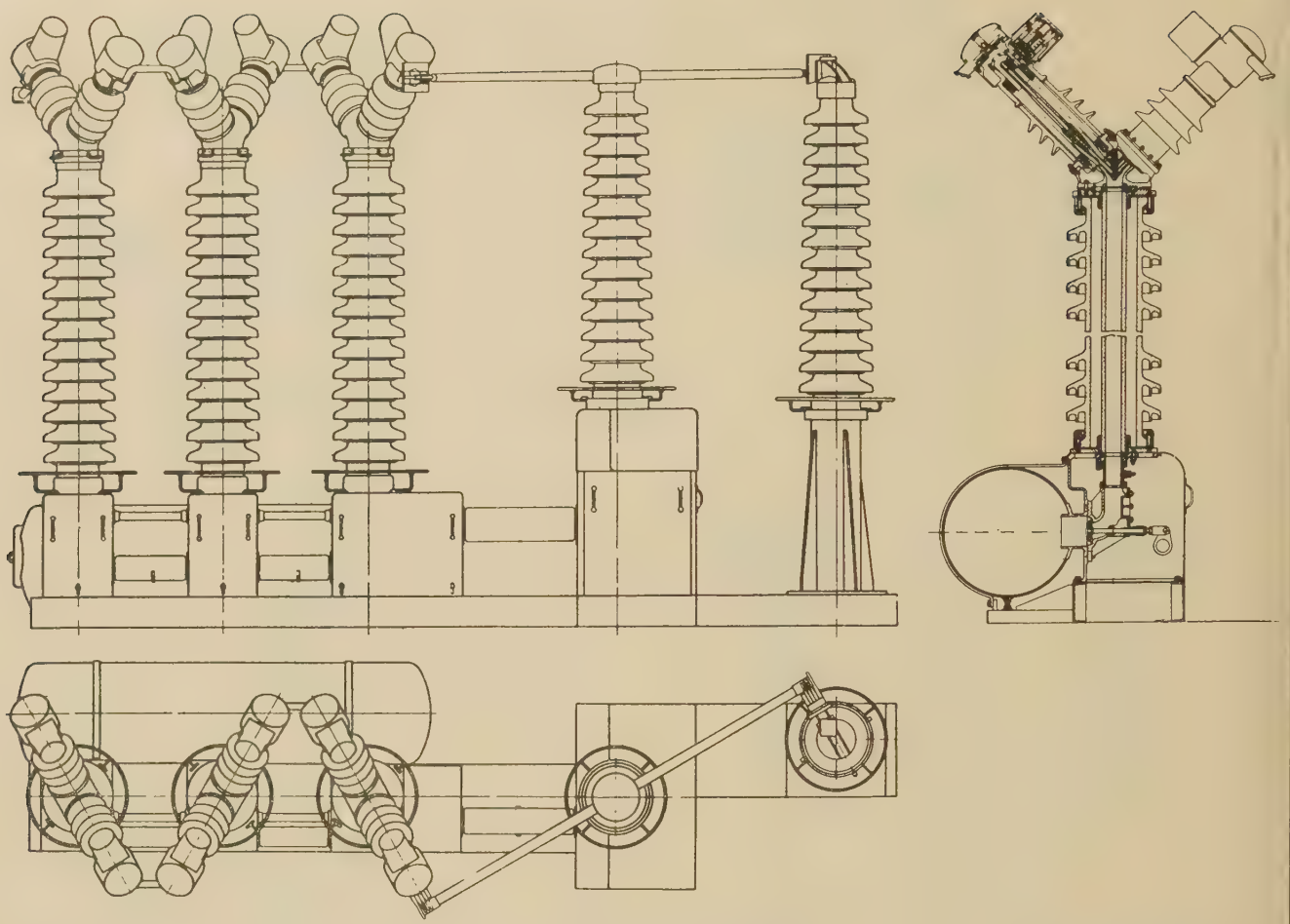


Fig. 30.—275 kV 7 500 MVA air-blast circuit-breaker with six breaks arranged horizontally, with capacitance voltage grading and sequence-switch motor mounted in chassis.

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Paper No. 1927 M
Nov. 1955

A NEW METER FOR THE KILOVOLT-AMPERE-DEMAND CHARGE

By P. BAXTER, Associate Member.

(*The paper was first received 2nd November, 1954, and in revised form 29th July, 1955. It was published in November, 1955, and was read before the* North-Western Measurements Group *22nd November, 1955, and the* Measurement and Control Section *17th January, 1956.*)

SUMMARY

The paper states that the introduction of an electricity tariff based in part upon a maximum apparent-power demand (VA m.d.), creates the need for a meter to measure apparent energy in a manner fair and just to all concerned. It gives two definitions for 3-phase apparent power and selects one as the more suitable basis for assessment of a maximum-demand charge.

A brief description is given of a Merz demand mechanism, which registers maximum demand (m.d.) from integrations made over definite time intervals. Reference is made to the difficulties of integrating 3-phase apparent energy (VAh) and these difficulties are held to be primarily responsible for the introduction of alternative methods of m.d. charging. Some of the alternative methods are briefly compared with that of the maximum-apparent-power-demand charge, colloquially known as the kVA charge, in order to explain why so many attempts have been made to produce a true 3-phase apparent-energy meter. The paper recognizes that some very ingenious meters have already been designed but suggests that none is entirely satisfactory for industrial applications. It shows how recent developments have made possible the introduction of a new type of apparent-energy meter based on an entirely new principle.

A description is given of a new type of volt-ampere indicating instrument, and this provides an introduction to a treatise on the new apparent-energy meter, whose main components are a dry plate rectifier, a transductor and an induction-type integrating meter.

A bibliography is included to indicate the background of knowledge and opinions which influenced the development of the meter.

Appendices deal with the interpretations of 3-phase volt-amperes, the voltage representation of a 3-phase system, and—with the aid of oscillographs—describe the operation of the meter components.

(1) INTRODUCTION

The rate at which the consumption of electricity is increasing imposes severe burdens on distribution networks, and frequently equipment has to be duplicated to prevent overloading. Improved efficiency may often be sufficient to prevent this overloading, and consumers are being encouraged, by the more general application of m.d. charges, to reduce their peak loads. Also, since loads at low values of power factor impose greater burdens on supply systems, an m.d. charge which increases when power factor is low assists in reducing these peak-load burdens.

Of the many forms in which m.d. charges have been applied, the "kVA charge" seems to be the fairest, and the considerable increase in the number of apparent-power m.d. meters installed tends to confirm this view. This trend has encouraged meter engineers to renew their efforts to design true meters of that type.

(2) 3-PHASE APPARENT-POWER MAXIMUM DEMAND

Before attempting to measure any quantity a clear definition of the quantity must be established. Some definitions depend upon the purpose for which the measurement is being made; for example, the weight of a material purchased may be expressed as its weight when purchased, or prior to evaporation, and may or may not include packing. In all cases the purchase price includes transport which would normally be based upon packed weight and dimensions. Electricity is no exception; most large consumers who are charged according to the total energy supplied also pay a periodic bill which is based on the heaviest load delivered. Although some tariff designers still prefer to have this load measured in terms of total power (kilowatts), there seems to be a general tendency towards the adoption of total apparent power (kilovolt-amperes) as the basis for the charge. The reasons for this may be that consumers are thereby encouraged to take their loads at high values of power factor, or that expenses associated with distribution systems, which are a function of the volt-ampere rating of the system, are increasing in relation to the expenses associated with generation. It seems, therefore, that the assessment of m.d. charges on the basis of apparent power has come to stay and that meters must be provided for the purpose.

Since electrical equipment will withstand overloads of short duration it is reasonable to assume that the expression maximum volt-amperes should signify, not an instantaneous value, but an average measurement over a definite time interval.

A consumer's apparent-power maximum-demand charge is introduced to recover expenses associated with the total volt-ampere capacity of the supply system required to carry the load. A supply system generally comprises three phases, and the total energy consumed is the arithmetical sum of the energy taken from all phases. Likewise, the total apparent energy is the arithmetical sum of the volt-amperes taken from all phases.

Meters which do not comply with this principle may not be strictly accurate when measuring the apparent power transmitted through a system, particularly when heavy single-phase loads cause a 3-phase 3-wire system to be unbalanced. There are, for example, several types of meter in which phase-angle relationships between voltage and current are employed, on the basis that any lagging reactive energy in one phase is provided by leading reactive energy in other phases, and only the difference between them is measured. Maximum-demand charges based on such meters are fair to all consumers only when each load is reasonably balanced and when the value of power factor remains reasonably constant during the period of maximum demand.

There are therefore two basic types of meter: one which employs phase-angle relationships to derive a vector-sum total of volt-ampere-hours, and one which measures the arithmetical sum of the apparent energy through all phases. Except when loads are badly unbalanced, the difference between the two methods of measurement is very small (see Section 8.1).

(3) EXISTING METERS AND PREVAILING MAXIMUM-DEMAND CHARGES

(3.1) The Maximum-Demand Indicator

The type of m.d. indicator in general use embodies a Merz demand mechanism geared to an integrating meter. The mechanism is in fact an integrating clock with one hand which drives a friction-held pointer over a scale of about 300°. The hand or driving pointer is automatically reset to zero at the termination of a definite time interval. The driven pointer remains in the maximum position until it is either driven to a higher position at a succeeding interval, or reset at the termination of the

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assessment period. In this way, the maximum quantity measured is averaged by integration over a definite time interval, and charges made are based on the highest value of the quantity taken within an agreed assessment period.

(3.2) The Kilowatts-Maximum-Demand Charge

Because of the relative simplicity of the energy meter, use is often made of a kilowatts-maximum-demand indicator to assess distribution charges. Consumers who then take the trouble to ensure that their load is reasonably balanced and at a power factor as high as is practicable inevitably pay an unfair proportion of such charges. In order to illustrate this, two typical consumers will be considered. Both consume the same number of units and have identical readings of kilowatts maximum demand. The first takes a balanced load at unity power factor but the second takes a single-phase load across phases at a power factor of 0·866. It will be seen that by kilowatt-maximum-demand measurement, although both pay the same distribution charges, the equipment required to supply the second is twice as large as that required to supply the first. Alternatively, if the second load is balanced, but at a power factor of 0·5, the equipment required is again twice as large as for the first consumer. If the total system output is taken by these two consumers and they are charged on a kilowatts-maximum-demand basis, the annual distribution costs will be shared equally by the two; whereas the first should pay much less than the second.

(3.3) Alternative Maximum-Demand Charges

In the construction of m.d. tariffs their designers were forced to consider the types of meter available for their assessment. Suitable apparent-power m.d. meters were unobtainable and several types of tariff were introduced which, although assessable by the use of conventional meters, could not readily be understood by consumers.

Some such tariffs employ a value of average power factor established over an assessment period by the use of energy and reactive-energy meters. This value of power factor, explainable only when loads are balanced, is used in conjunction with a value of m.d. in kilowatts measured over one particular time interval of an assessment period.

Others incorporate a measurement of reactive-power m.d. which must be very difficult for most consumers to understand, and it is not surprising that, in many cases, legal agreements have been necessary before such tariffs could be applied.

(3.4) Kilovolt-Ampere Maximum-Demand Meters

Integrating meters for apparent energy (kVAh) are much more complex than energy meters. They are usually much larger and more expensive, their standard of accuracy in some designs is inferior to that of energy meters and certain types are accurate only within declared limits of power factor or voltage. The most popular has been the limited-power-factor-range type. This is essentially a kilowatt-hour meter and therefore falls in the vector sum class. It is connected and calibrated to integrate at a maximum rate when the load power-factor is of some predetermined value. Meters of this type are supplied for use within a marked range of power factor over which their accuracy is reasonable; outside this range quite large errors are introduced. It is therefore necessary to predict the power factor range of the load to be metered.

Another vector-sum class comprises two complete integrating meters in one case. One is a kilowatt-hour meter and the other a reactive-kilovolt-ampere-hour meter. Coupling the two integrators is a system of gearing which includes a mechanical apparent-energy (kilovolt-ampere-hours) integrator. The accuracy of the latter is, within reasonable limits, unaffected by the value of power factor between unity and zero lag.

There is also the current-operated induction type of maximum-demand indicator. This is obtainable with compensation for slight variation of voltage. Although such a meter is not provided with an integrator, the maximum-demand indicator is of the Merz type and has a scale calibrated in kilovolt-amperes. Since such meters do not depend upon phase relations for their operation they are in the "arithmetical sum" category.

None of these meters has received the general acceptance given to the induction-type energy meter. Hence the introduction of a new apparent-energy meter which may ultimately receive universal recognition.

(4) A NEW 3-PHASE VOLT-AMPERE INDICATOR

By the use of current transformers and rectifiers, 3-phase currents can be summated to provide control current proportional to the arithmetical sum of the three phase-currents.

Similarly a 3-phase voltage can be made to produce a control current by the use of three separate resistor banks connected to the three phases, with a small 3-phase rectifier forming the neutral of a star connection. A coil connected to the d.c. terminals of the rectifier would carry a direct current proportional to the 3-phase voltage.

A single-element dynamometer wattmeter connected to such a circuit can be calibrated in terms of 3-phase volt-amperes, and Fig. 1 shows such an arrangement which has proved to be a

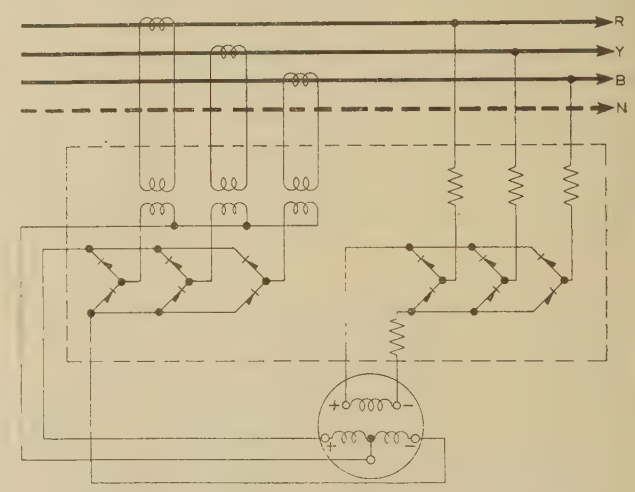


Fig. 1.—Circuit diagram of 3-phase volt-ampere indicator.

very accurate and stable instrument. It is submitted that there are many circuits for which a control engineer would prefer to have a kilovolt-ampere indicator in place of the usual wattmeter.

By careful selection of components it has been found possible to calibrate a precision 3-phase volt-ampere indicator to a degree of accuracy and stability normally associated with precision wattmeters. Such an indicator can be used to simplify the calibration of apparent-energy meters.

(5) A NEW 3-PHASE APPARENT-ENERGY METER

(5.1) Development

Realizing the necessity for a meter to measure unbalanced 3-phase apparent energy, which would be in keeping with the normal energy meter, the author searched, as many have done before him, for a method by which this ideal could be achieved.

The problem was to develop a true meter from which the

maximum demand in volt-amperes could be ascertained. It was therefore necessary to provide means whereby the currents in the three phases could be added arithmetically and applied to the meter in such a way that the product of this addition and the system voltage would be integrated.

A d.c. watt-hour meter, when connected in place of the indicating instrument in Fig. 1, behaved as an apparent-energy meter, but the practical difficulties associated with such a combination discouraged its use. Further investigation, however, led to an attempt to replace the d.c. watt-hour meter by a single-element induction-type energy meter. The key was found in the use of a transductor which converted rectified alternating current of variable power factor to alternating current with its phase fixed in relation to an alternating voltage.

The transductor was used as a d.c. transformer with its secondary windings energized by an alternating voltage, which also provided the output energy to operate the meter. Such a transductor operates with the same degree of accuracy as an a.c. instrument transformer. Its primary winding carries direct current which is represented in its secondary circuit by alternating current, the average value of which is a true measure of the primary current. If, therefore, the sum of the rectified phase currents is applied to the primary, and the secondary current is passed through the current coil of an induction watt-hour meter, the meter current will be a function of the total 3-phase current. If the voltage coil of the watt-hour meter is connected across two phases of the 3-phase circuit, the meter will then integrate at a rate which is a function of the volt-amperes of the circuit being metered (see Fig. 2).

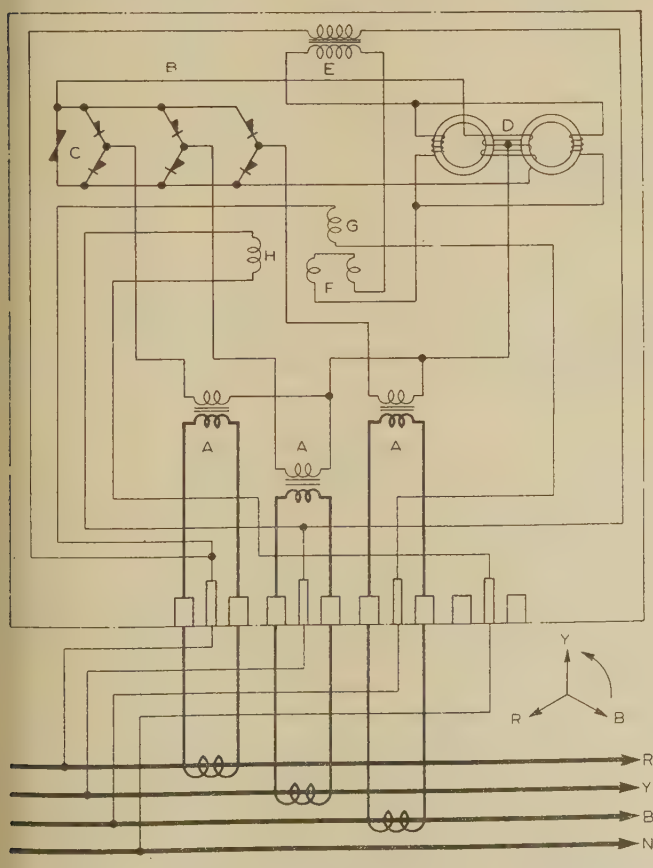


Fig. 2.—Circuit diagram of 3-phase apparent-energy integrating meter.

A. Auxiliary current-transformers.
B. 3-phase rectifier.
C. Metrosil unit.
D. Transductor.
E. Auxiliary voltage-transformer.
F. Meter current-coil.
G. Meter voltage-coil.
H. Synchronous motor.

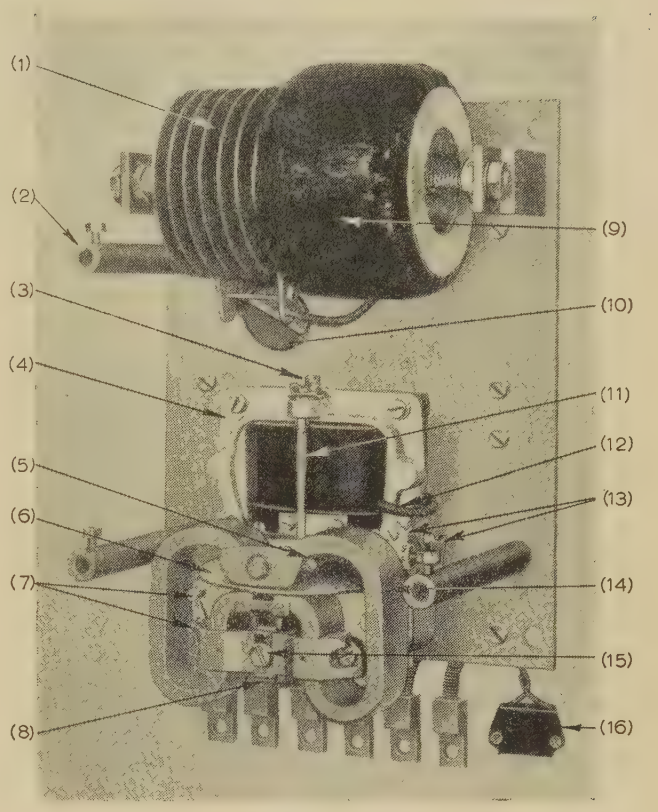


Fig. 3.—Internal arrangement of meter components.

1. 3-phase metal rectifier.
2. Sockets for indicator mechanism.
3. Spring clamp for top bearing.
4. Die-cast meter frame.
5. Locking screw for low-load adjustment.
6. Aluminium disc.
7. Coarse speed adjustment moving brake-magnet system.
8. Micrometer speed adjustment by magnetic shunt across brake-magnet poles.
9. Transductor.
10. Metrosil disc.
11. Pinion drive to indicator mechanism.
12. Low-load compensator.
13. Low-load adjustment.
14. Twin brake-magnets.
15. Locking screw for micrometer speed adjustment.
16. Socket for resetting-mechanism motor.

Development along these lines finally resulted in the production of a polyphase apparent-energy meter (see Fig. 3), comparable in size and performance with a normal polyphase energy meter. The auxiliary voltage transformer and the three auxiliary current transformers are mounted as a compact assembly on the back of the chassis.

(5.2) The Voltage Components of a 3-Phase System

It will be understood that although load currents may be unbalanced and the system voltage variable by as much as $\pm 10\%$, the three line voltages remain balanced to within very close limits. For all practical purposes, therefore, a measurement of the line voltage is directly proportional to the voltage to neutral (see Section 8.2).

The new meter utilizes this fact and its one voltage coil is connected across two of the three phases. The small improvement in overall accuracy which could be achieved by the use of a meter having three elements each connected to its own phase does not justify the large increase of cost and size which would ensue.

(5.3) Design Details

The single induction-pattern meter element used in the new meter differs only slightly from those which are used in energy meters. Its current coil is energized from the secondary winding

of a small voltage transformer through the a.c. windings of a small transductor. The primary winding of this voltage transformer, and also the voltage coil of the meter, are wound for connection to the supply-voltage or mains-voltage transformer. The primary winding of the transductor carries the direct current from a 3-phase rectifier fed from the secondary windings of three auxiliary current-transformers, with their primary windings connected into the three main lines, or to the secondaries of main current-transformers. The meter element, the four auxiliary transformers, the rectifier and the transductor are all mounted in an ordinary polyphase meter case.

(5.4) The Rectifier and its Auxiliary Current-Transformers

The type of rectifier used is referred to in Section 8.3, which describes the method used to rectify currents flowing in three lines of a 3-phase circuit. It will be noted that three auxiliary current-transformers are connected between the rectifier and the main circuit or main current-transformers. These auxiliary current-transformers are necessary to provide the required insulation between the three main current circuits and to permit the use of a comparatively small rectifier. So that the meter will withstand at least thirty times normal-load current for half a second, the auxiliary transformers are designed to saturate, and this feature, together with a non-linear resistor connected in parallel with the rectifier, prevents damage to the meter when short-circuits occur on a consumer's installation.

The summated rectified current is applied to the primary winding of the transductor and a tapping at the central point of this winding provides a neutral point for the auxiliary current-transformer secondary windings.

(5.5) The Transductor

The transductor comprises two strip-wound nickel-alloy cores, each of which is wound with the required number of turns to form the a.c. winding. These may be connected either in series or parallel, but the parallel condition is used because the a.c. output is more suitable for the operation of the meter. This output is controlled by, and is directly proportional to, the summated rectified line currents, which pass through the primary turns embracing both cores.

It is not proposed to describe the mechanism of the transductor because this has already been covered by previous writers.[10,11] It is desirable, however, to state that the average a.c. output is a linear function of the d.c. input even when the alternating energizing voltage varies. In other words, the transductor is a current transformer for direct current, so designed that the alternating magnetizing current is less than 1% of the current which it will pass at full load.

Oscillograms show that the secondary current is in the form of pulses which are phase displaced in relation to the voltage across the transductor, and it will be seen that the current lags behind the voltage by an angle varying slightly with the load current (see Figs. 4–8). Since this current is to be applied to one coil of the integrating meter, its phase is of importance to the ultimate accuracy of measurement, and in order to keep the phase change to a minimum the power output taken through the transductor at full load must be only a small fraction of the maximum power it is capable of passing.

(5.6) The Combination of Rectifier, Transductor and Induction Meter as an Apparent-Energy Meter

As already explained, the 3-phase load currents are arithmetically summated by means of a dry plate rectifier, which provides a direct current (I_{DC}) proportional to the sum of the three phase currents (I_R, I_Y and I_B). This direct current passe through the transductor primary winding, and the resultin secondary current which passes through the meter current co lags behind the applied voltage by approximately 85°. Also, a described in Section 5.5, this phase angle varies slightly wit change of load current, and in order to minimize the effect c this variation, the effective magnetic flux of the voltage coil mus lag 90° behind the effective current-coil magnetic flux when th load current is about 50%. This is also a condition which provide maximum driving torque and is therefore a very desirable featur (see Section 8.4).

There are several methods by which the active magnetic flu of induction-meter electromagnets can be adjusted, but as thes methods are well known it is not proposed to enlarge on the It is sufficient to state that, in order to provide the require magnetic flux relation, the transductor is energized by a voltag which leads by 60° the voltage applied to the meter voltage-co (see Fig. 2). The further 25° or so is then provided by phas displacing the effective magnetic fluxes of the meter and also t the phase angle of the auxiliary voltage-transformer.

With the meter compensated in this way so that its torque highest, proportionally, at about 50% load, its torque at low loads would be lower owing to the slight phase variation of t transductor current, but this is corrected by adjusting the met to have a forward torque on voltage alone. This torque (which a function of the square of the voltage) would cause registratio on no load, and in order to prevent this the disc has six ant creep holes. These holes also have a braking effect proportion to the square of the voltage, and this feature minimizes erro which tend to occur at low loads when the system voltage varie

A typical meter has an error range of ±1·5% from 5 to 12 load at any value of power factor with the current either leadi or lagging. It will withstand double load current continuous and a short-circuit current of at least 30 times normal for 0·5 se Errors resulting from variation of voltage, frequency or tem perature do not exceed the limits usually associated with indu tion-type energy meters.

(6) ACKNOWLEDGMENT

The author wishes to express his gratitude for the advice an help of Mr. T. W. Ross during the development of the met and in the preparation of the paper. Permission by th Metropolitan-Vickers Electrical Company, Ltd. to publish th paper is also gratefully acknowledged.

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(8) APPENDICES

(8.1) The Difference between Two Methods of 3-Phase Apparent-Power Interpretation and Measurement

In method (*a*) let the total 3-phase apparent power be expressed as $\sqrt{[(3VA\cos\phi)^2 + (3VA\sin\phi)^2]}$, where V is the voltage to neutral and A is the current in each phase in amperes, the two terms of the expression being respectively the quantities measured by a wattmeter and a reactive-power meter. Where $\cos\phi$ is the power factor of a balanced 3-phase load, this expression requires no explanation. If, however, the load is unbalanced there may be three separate values of ϕ, and when loads are widely different the expression cannot be applied to a system of three phases, which would be transmitting an apparent-power load different from that of the consumed load. For example, a non-inductive load across two phases imposes a burden on each of two phases of the system. In one phase the power factor is 0·866 lag and in the other, 0·866 lead. The reactive-power meter in method (*a*) measures only the difference between the leading reactive power in one phase and the lagging reactive power in other phases. The indication is therefore of zero reactive power, even though two phases are transmitting power at 0·866 power factor.

In method (*b*), the total 3-phase apparent power is the sum of the volt-amperes transmitted through all phases, and is expressed as $VA_{total} = V_RA_R + V_YA_Y + V_BA_B$ (where A and V are the values measured respectively by ammeters in each phase and by voltmeters connected from each phase to neutral). By the use of a common reference voltage the value of VA_{total} is unaffected by load unbalance or by the position in the distribution system at which the measurement is made.

The difference between method (*a*) and method (*b*) becomes significant only when 3-phase 3-wire loads are excessively unbalanced. Table 1 shows the result of an actual test and the values obtained can also be proved by mathematical analysis. From this it will be seen that even if 60% of the total load is unbalanced the difference is less than 2·3%.

Table 1

RESULTS OF TESTS ON TWO 3-PHASE METERS ON A 3-WIRE SYSTEM. (NON-INDUCTIVE LOADS ACROSS PHASES)

Phase current			Meter speeds		
R	*Y*	*B*	Meter *a*	Meter *b*	Percentage difference, b=100
amp	amp	amp	r.p.m.	r.p.m.	%
5	5	5	26·0	26·0	—
5	6	6	29·4	29·5	0·4
4	6	6	27·4	27·8	1·4
2·5	5	5	21·1	21·6	2·3
0	5	5	15·0	17·3	13·3

In meter (*a*) $VA_{total} = \sqrt{(P^2 + Q^2)}$ (i.e. vector sum).
In meter (*b*) $VA_{total} = V_RA_R + V_YA_Y + V_BA_B$ (i.e. arithmetical sum).

(8.2) Voltage Representation of a 3-Phase System and its Effect on the Accuracy of the Meter

A 3-phase system has voltages to neutral V_R, V_Y and V_B. When these are equal and spaced at 120° the system voltages are balanced and a voltage measurement between phases accurately represents the values of voltage to neutral. Even though voltages to neutral are sometimes unbalanced by as much as 3% it will be found that any value of voltage between phases still represents the average voltage to neutral within 1%.

Table 2

OBSERVED ERRORS IN THE NEW VOLT-AMPERE-HOUR METER OPERATING WITH THE SYSTEM VOLTAGE UNBALANCED

3-phase system-voltage unbalance	Meter error
	%
Balanced	+0·4
$V_R - 10\%$, or both V_B and $V_Y + 10\%$	−1·1
$V_R + 10\%$, or both V_B and $V_Y - 10\%$	+1·8
$V_Y - 10\%$, or both V_R and $V_B + 10\%$	+2·7
$V_Y + 10\%$, or both V_R and $V_B - 10\%$	−2·7
$V_B - 10\%$, or both V_Y and $V_R + 10\%$	−1·1
$V_B + 10\%$, or both V_Y and $V_R - 10\%$	+2·3

The parameters of the new meter are such that the error is even less than 1%, and actual tests taken with the meter on a system with its voltages to neutral unbalanced by 10% show that in no case did the error exceed 2·7% (see Table 2).

(8.3) Dry Plate Rectifiers and their Use in the Meter

Although the inclusion of copper-oxide rectifiers in measuring circuits for converting alternating current into direct current is well established, their very low maximum plate-voltages introduce difficulties when they are used in industrial current-measuring circuits where the possibility of overload is always present.

Selenium rectifiers, whose plates will withstand a voltage in excess of 20 volts are more suitable for industrial use, and extensive life tests on many thousands of these plates have proved that selected rectifiers are entirely satisfactory for measurement purposes. Circuits must be designed so that characteristic variations in the forward resistance and the reverse leakage current will have no significant influence on the ratio of alternating to direct current values.

The 3-phase bridge rectifier embodied in the meter is of the selenium type. It is connected between three current transformers and a control coil of (N_{DC}) turns. A centre tap on the control coil is connected to the star point of the star-connected transformers (see Fig. 2).

This arrangement ensures that the d.c. ampere-turns ($I_{DC}N_{DC}$) are proportional to the sum of the current-transformer secondary currents I_R, I_Y and I_B. The actual relation can be expressed as $I_{DC}N_{DC} = 0{\cdot}45N_{DC}(I_R + I_Y + I_B)$.

(8.4) Meter Element Operation by the Transductor

The average number of control or primary ampere-turns on the transductor ($N_{DC}I_{DC}$), as described in Section 8.3, is equal to $0{\cdot}45N_{DC}(I_R + I_Y + I_B)$. The basic equation for a parallel-connected transductor, with its a.c. voltage and secondary impedance within specified limits, is given by $N_{AC}I_{AC} = 2N_{DC}I_{DC}$, where N_{AC} is the number of turns per core and I_{AC} is the average value of the secondary current pulses. It follows that $I_{AC} = 0{\cdot}9\dfrac{N_{DC}}{N_{AC}}(I_R + I_Y + I_B)$. Thus I_{AC} is proportional to the sum of the alternating currents.

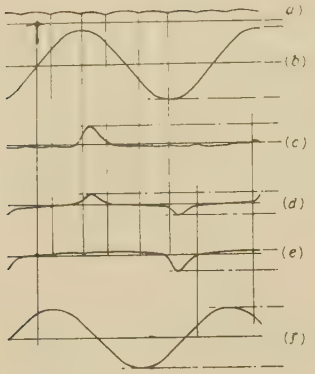


Fig. 4.—Operation of meter components on 25% load.

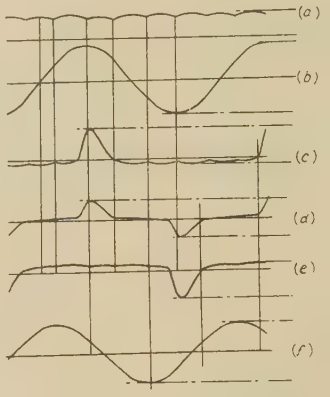


Fig. 5.—Operation of meter components on 50% load.

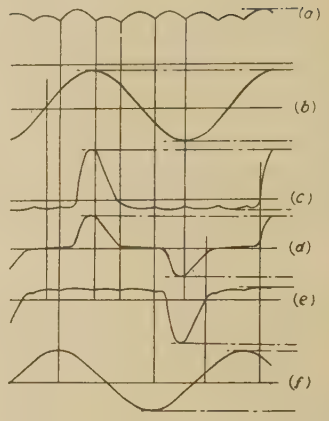


Fig. 6.—Operation of meter components on 100% load.

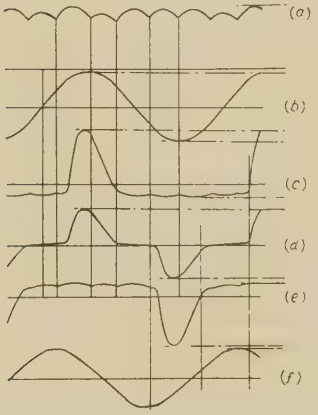


Fig. 7.—Operation of meter components on 125% load.

(*a*) Rectified 3-phase current, 0·6 amp/cm.
(*b*) Meter element voltage, 132 volts/cm.
(*c*) Current through left-hand transductor coil, 1·3 amp/cm.
(*d*) Meter element current (total transductor output), 2·8 amp/cm.
(*e*) Current through right-hand transductor coil, 1·3 amp/cm.
(*f*) Voltage applied to transductor circuit, 2 volts/cm.
Ordinate scales refer to original records; the figures are approximately one-third original size.

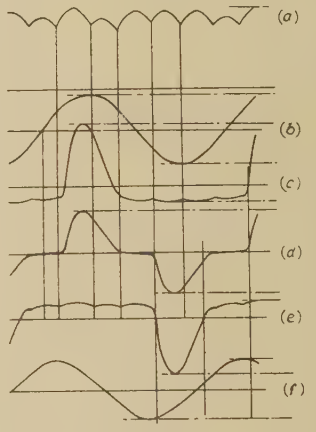


Fig. 8.—Operation of meter components on 160% load.

This alternating current, I_{AC}, passes through one coil (C) of the induction-meter element, with its other coil (S) subjected to the system voltage, V. Phase selection and other well-known phase-adjusting methods are used to ensure that the pulse I_{AC} occurs at the instant when V is at its peak value, V_{max}.

Let ϕ_C = The instantaneous value of the flux due to coil C.
ϕ_S = The instantaneous value of the flux due to coil S.
i_C = The instantaneous value of the eddy current in disc induced by ϕ_C.
i_S = The instantaneous value of the eddy current in disc induced by ϕ_S.

Then the instantaneous rotor torque is proportional to $\phi_S i_C + \phi_C i_S$. Although ϕ_S and i_S are sinusoidal, ϕ_C and i_C are only part-sinusoidal since they result from I_{AC}, which is in the form of pulses existing for the very short intervals during which ϕ_S can be considered at its maximum value ϕ_{Smax}. The avera torque produced during these intervals is therefore proportion to $(\phi_{Smax} i_C)$ or $V/\sqrt{3}(I_R + I_Y + I_B)$, since $V/\sqrt{3}$ is represent by ϕ_{Smax}, which is proportional to the measured voltage, and is induced by ϕ_C which is proportional to I_{AC} and to the su $(I_R + I_Y + I_B)$.

In practice, when the meter is on overload, the pulses I_{A} persist for an interval during which V falls below its peak val V_{max}. At very low loads the pulses are of very short duratio and they occur at an instant when V has fallen slightly belo V_{max} (see Figs. 4–8). As described, these characteristics tend introduce slight negative errors, particularly when loads a below 20%. However, by the use of compensating devic the overall performance of the new apparent-energy meter similar to that of the well-known induction-pattern ener meter.

DISCUSSION BEFORE THE MEASUREMENT AND CONTROL SECTION, 17TH JANUARY, 1956

Mr. D. J. Bolton: The question of how to charge for bad power factors is one of the great unsolved mysteries of electricity supply. Of the 16 Area Boards concerned with the sale of electricity in March, 1955, I find that there were no less than five different ways of dealing with the problem. The Central Electricity Authority, in their bulk-supply tariff, disregard power factor entirely. As regards the retailing boards who have standardized a two-part tariff, three of them base the standing charge on apparent power, five use (or threaten to use) a power-factor adjustment of one kind or another in the kilowatt assessment, whilst one makes a charge for reactive-power demand. one case the power-factor adjustment is applied also to the blo tariff. So we have a somewhat complex picture, but the auth can at least claim that the basis for which his meter is design represents the largest single method for power-factor penalizatio

If we leave the factual position and come to the theoretic justification for the use of that type of meter, the case is not qu so strong. The standing charge of the two-part tariff has collect the maximum-demand charge of the bulk supply as w as covering the demand-related costs of the Area Board itse

Thus only about half of this standing cost is affected by power factor, and even this not so strongly as the author implies. It is true, as the author states, that a balanced load with a power factor of 0·5 or a badly unbalanced load with a power factor of 0·866 requires twice as much distribution equipment as one with a unity power factor. But is it not somewhat unrealistic to suppose that, in fact, twice the equipment will be provided? Surely if a Board were faced with this situation they would find some more economical solution than duplicating the whole of their equipment.

Historically, the kilovolt-ampere basis preceded the kilowatt basis. The original Hopkinson two-part principle was implemented by means of the Wright meter, which was a thermal sluggish maximum-reading ammeter. The thermal principle had the advantage of an inverse time-lag characteristic, and of course, looked after power factor. Unfortunately, besides neglecting the voltage, it lacked precision. One knew that it was measuring the right thing, but nobody could state precisely *what* it was measuring.

Then Merz produced an exact mathematical piece of clockwork, but since it was linked with an energy meter it took no account of power factor. The author has now repaired this omission, and has devised an ingenious way of using the Merz time-interval principle to record volt-amperes instead of watts.

With regard to the rather complicated combination described in Section 5.6, whereby alternating current is rectified to direct current and then transducted back to alternating current, each of these conversions means that a certain amount of adjustment and compensation has to be provided. One would need to have more detailed figures than the author is able to give in his paper before being satisfied that all these adjustments were going to operate correctly.

I notice, for instance, that the torque is highest, proportionally, at about 50% load, and a positive torque addition is needed at low loads. That is provided by a voltage torque independent of load. But if 50% load gives the maximum torque per ampere, will not an adjustment also be needed on high loads? Moreover this adjustment requires a counter-adjustment in the form of holes punched in the disc to give an anti-creep mechanism. This, in its turn, must be sufficiently powerful to prevent shunt-running when the voltage is somewhat high, but not enough to prevent registration on low loads and voltages.

Mr. J. W. Carter: In many instances the recent re-organization of tariffs required a change from kilowatt to kilovolt-ampere demand metering, which provided an opportunity to compare their respective merits from practical experience with both methods. For those who deal with day-to-day matters arising from meters in service, the most striking difference is the simplicity of the kilovolt-ampere tariff in being implemented from meter readings that can be checked by the consumer and are directly connected with the figures of his account, whereas kilowatt tariffs are usually associated with an indirect kilovolt-ampere charge derived from an adjustment for power factor which involves a calculation that is quite obscure for the vast majority of consumers and is an objectionable feature in a commercial transaction.

In the absence of an authoritative definition of polyphase apparent power, there is a choice between vector-sum and arithmetical-sum measurements. Complete uniformity can be attained by using one method only, but in dealing with both large and small supplies this principle is not easily applied. It is fortunate, therefore, that loading conditions at times of maximum demand are hardly likely to produce the differences suggested by theoretical considerations. A comprehensive use of the Transva meter might be possible, but would depend upon its suitability for summation metering, which, for the impulse method, would entail a further burden on the single-element meter.

Kilovolt-ampere maximum-demand meters suffer from the great variety of ways in which their scales are marked. Benefits would follow a measure of standardization, and as the Transva meter has advanced a step in this direction, a reference to scale marking would be an interesting addition to the paper. The author has given an assurance about the effect of short-circuit conditions on the meter, but on this important point, supporting test data would be very welcome.

Mr. C. Ryder: The author's device would seem to lend itself admirably to summating two or even three circuits. In starting with the advantage of obtaining the measurement of a 3-phase circuit on one single meter element, it would seem only to be necessary to have two or three elements with the discs coupled together to summate two or three circuits. A further advantage would seem to be that the mechanism has not been increased.

There is the other alternative of electrical summation, where the current in the circuits can be fed through the rectifiers on to the common primary winding of the transductor. If that is possible, the summation arrangements would not be limited merely to two or three circuits—the meter would lend itself to being extended to almost any number of circuits.

I heard recently of some consumers who had premises that had grown more or less randomly over the years. As additional buildings had been obtained for manufacturing purposes, the electrical supply had been extended by creating additional self-contained small distribution systems. The consumer was thus left with the problem of dealing with a number of isolated metering circuits. Not only is the consumer bothered, but the supply authority must also be concerned, because whenever one is applying tariff penalties in terms of power factor—or it may be bounties—the question arises of how to get an accurate assessment of simultaneous maximum demand on a number of separate metering circuits. I should like the author to comment on the possibilities of modification or application of the new meter to summating purposes.

Mr. F. G. Talbot: In 1929 E. W. Hill pointed out anomalies and ambiguities that can occur through the indiscriminate use of different definitions of apparent power (see Reference 1 of the paper).

Little progress has since been made towards resolving this fundamental difficulty. In fact, owing to the more widespread use of plant with non-linear and other characteristics, the position is now worse than it was at that time. B.S. 205 still gives three definitions for total equivalent volt-amperes.

The delay in reaching a solution has certainly not been due to any lack of ingenuity on the part of meter designers. Many types of kVA-meters are manufactured, some of which give the vector summation of the phase currents, and others the arithmetic sum; some cater for unbalanced factors by including negative-sequence currents, some include distortion power, and others do not discriminate in this respect. In some designs, ingenious mechanisms are included to give a true indication of apparent power with varying power factor over the time-integration period, at the same time ignoring harmonic-distortion currents which, in certain circumstances, can be much greater in their effect than power-factor variation over short periods.

Some engineers and others have been concerned about the characteristics of the time-integration period, i.e. whether it should be linear, or exponential to follow the heating characteristics of the load, and one American firm has constructed a mechanical device to simulate this latter characteristic.

It seems that it is time to evaluate the relative economic importance of the various factors I have mentioned. Until this is done, money will continue to be spent on ingenious devices in what might prove eventually to be unsuccessful attempts to provide a meter for the perfect tariff.

It would add to the value of the paper if more test figures were included, e.g. a kVA indicator should, at least, measure the product of r.m.s. voltage and r.m.s. current, and it would be interesting to know how the meter described would stand up to the tests described in Dr. Dannatt's paper.*

Mr. A. R. Mowl: With reference to Fig. 1 of the paper, no provision has been made for smoothing the rectified currents which energize the wattmeter coils. Even with bridge-type 3-phase rectifiers there is an appreciable a.c. component, and if alternating current is present both in the fixed and moving coils of the wattmeter, a torque will be developed, the magnitude of which will depend upon the phase relationship of voltage and current in the polyphase circuit. As the frequency of the alternating components is six times the fundamental frequency, it seems probable that the error of the volt-ampere indicator could swing from maximum negative to maximum positive and back again while the load phase angle changed 60°. This does not appear to be consistent with the statement that the indicator can be calibrated to a degree of accuracy normally associated with precision wattmeters.

The apparent-power-demand meter, which forms the main subject of the paper, does not appear to be liable to phase-angle errors in the same way as the indicator. However, I should like to know whether tests have been carried out to determine the effect of small changes in phase angle. Errors of this kind, if they exist, would probably be unimportant in normal operation owing to the averaging effect of the demand mechanism on circuits with varying power factor, but in the test room, where the power factor is likely to remain steady during short-period tests, dependence upon power factor may cause embarrassment.

It would also be useful to have data obtained from tests with varying voltage, frequency and temperature, in order to compare the performance of this meter with others using different principles of operation.

Mr. S. F. Knight: The author has shown how, with balanced loads, the ripple in the transductor control current, which is seen in each output circuit, does not appear in the meter current coil. Does this still hold true on unbalanced loads when the ripple is very much increased, or has it been found necessary to smooth the direct current to cover such conditions?

The current that the transductor will pass on no load—about 1% of the full-load current—would appear to be an embarrassment at low loads on the meter. This could be overcome by the use of a bridge circuit. The secondary winding of the auxiliary voltage transformer E in Fig. 2 of the paper would be centre-tapped and the transductor magnetizing current balanced against the current taken by a small choke. This would make the six anti-creep holes unnecessary, and should prove a better design.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. P. Baxter (*in reply*): There will always be differences of opinion regarding the construction of a tariff to ensure fair distribution of costs, and since we cannot hope to reach perfection it would seem that overall simplicity, uniformity and metering accuracy are the most important factors. It gives considerable satisfaction to have Mr. Bolton's agreement that the new meter is designed to suit the most common method of power-factor penalization.

Methods of compensating the meter are similar to those employed on all commercial meters, and negative errors at high loads are reduced by saturable magnetic shunts.

Mr. Carter's experience with several methods of applying a maximum-demand tariff is similar to those reported from several countries. Confidence in both the simple kVA maximum-demand tariff and the meter is shown by the large number of meters now in service.

Circuits known to be generally unbalanced have been metered over long periods by meters of several types, and identical records of maximum demand appear to prove Mr. Carter's opinion regarding the use of meters operating on either the vector-sum or the arithmetical-sum principle.

Over-current tests up to 30 times full load for $\frac{1}{2}$ sec were carried out on typical meters in which oscillograph shunts were introduced, and the rectifier plate voltage peak was less than the rectifier maker's recommended maximum. The meter performance after the test proved that no defects had been contracted.

Simultaneous maximum demand can only be established on a summation device, and Mr. Ryder envisages the use of a multi-element meter for this purpose. Such an arrangement has already been introduced for two circuits and is quite suitable for maximum-demand metering. For more than two circuits, impulse metering is the more accurate.

A treatise on the effect of non-linear loads on metering accuracy, referred to by Mr. Talbot, predicts errors introduced to energy and reactive-energy meters which are also applicable to the new meter.

It is agreed that there has been ambiguity associated with the definition of apparent power, applied to tariff metering of 3-phase supplies, but it would appear that 'total volt-amperes' is becoming the more popular definition since it is related more directly to costs.

Mr. Mowl's contention that some variation occurs in the accuracy of the kVA indicator is true; power-factor change varies its accuracy by less than 0·6%. The addition of smoothing reduces the error below 0·15%. This arrangement has been found to be quite satisfactory for short-period testing and is considered unnecessary for commercial indication.

The following test results are given at the request of Messrs. Talbot and Mowl.

A typical 3-phase volt-ampere indicator with smoothing calibrated to three dynamometer ammeters and three dynamometer voltmeters was accurate to ±0·3% at standard frequency and temperature. The measured characteristics were as follows:

Frequency from 45 to 55 c/s	0·1% change
Temperature coefficient from −5° C to +40° C	0·008% change per 1° C
Power factor over 360°	0·15% change
Voltage unbalance of 10%	0·5% change

A typical 3-phase VAh meter, operated at standard temperature, voltage and frequency, had the following load curve:

Load current	5%	10%	25%	50%	100%	125%
Error	+1%	0	+0·3%	+0·5%	0	−0·5

Measured characteristics were as follows:

Self heat	1·2% change
Frequency from 45 to 55 c/s	0·5% change
Temperature coefficient from −5° C to +40° C	0·05% change per 1° C
Power factor over 360°	0·5% change
Voltage unbalance of 10%	2·7% change (maximum)
Voltage variation of 10%	1% change

When loads are unbalanced the ripple referred to by Mr. Knight does not appear in the meter current coil and no smoothing is necessary. Whilst the bridge circuits he suggested do result in certain improvements, the present arrangement has a minimum number of components and is more satisfactory for large-quantity production.

* DANNATT, C.: 'The Metering of Mercury-Arc Rectifier Supplies and Outputs', *Journal I.E.E.*, 1937, 81, p. 256.

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AGE AND THE INCIDENCE OF FIRES IN ELECTRICAL INSTALLATIONS

By L. GOSLAND, B.Sc., Member.

(*The paper was first received* 15*th June, and in revised form* 16*th August*, 1955. *It was published in January*, 1956, *and was read before the* Utilization Section 19*th January, and the* North Midland Utilization Group 21*st February*, 1956.)

SUMMARY

The paper reviews data on the occurrence of fires due to defects in fixed electrical installations amongst a population of about 2·5 million consumers over the years 1951–53 inclusive. The correlation between age of installation and the incidence of fires is examined, and it is shown that for installations more than fifteen years old the incidence of fires is roughly proportional to the age of installation. There is no clear indication of any maximum safe life. Installations less than 15 years old are considered as a separate class, being subject to innovations in housing construction and installation practice. Incomplete data on the types of equipment revealed as defective and on the nature of the defects are reviewed. There is no clear indication that any one type of equipment is particularly subject to the effects of age. The most frequent primary cause of fire is defective wiring, and the most frequent secondary cause fortuitous contact between wiring or earth-continuity conductors and composition gas-pipes. Apart from the latter, there seems no single type of defect the elimination of which could lead to outstanding reduction in the incidence of fires.

(1) INTRODUCTION

In 1947, the Electrical Research Association Subcommittee V/B (Fire Risks) agreed that an answer was urgently required to the question posed by their Chairman, Mr. H. W. Swann, whether there was an age at which electrical installations, and particularly domestic installations, might be supposed to have reached the end of their safe useful life. It was at first thought that information might be gained by detailed study of particular cases of fires alleged to have been caused by electricity, but no practicable arrangement emerged. An alternative course was the detailed inspection of sample aged installations, but a pilot investigation in which the wiring and fittings in a large house due for demolition were thoroughly, and indeed destructively, examined, did not give encouraging results.

A third possibility was a more general attack using existing channels of information. If installations were becoming unsafe through age, it should be possible to demonstrate the fact by examination of statistics on failures.

One class of failure consistently reported is that giving rise to fires. Fire authorities have for some years past assessed and reported on the origin of all fires or manifestations giving rise to calls to fire brigades; 10% of all fires in buildings attended in 1946 were attributed in such assessments to electrical causes. If a suitably large group of installations of which the age distribution was known could be segregated, and the age of each installation causing a fire call determined, then the number of fire calls per ten thousand installations of each age group could be found, and significant variation of this figure with the year of the installation should indicate the effects of age.

This plan proved practicable, and—with the co-operation of the D.S.I.R. and Fire Offices' Committee Joint Fire Research Organization (J.F.R.O.) and of a number of British Electricity Area Boards—was put into effect. The paper describes the way in which the investigation was carried out, and the results obtained. In addition to the broad information which the work was primarily designed to produce, a good deal of detailed information on the causes of fires also became available. This also has been analysed so far as is possible.

(2) METHOD OF INVESTIGATION

Ten of the Area Boards, having substantial regions within which the annual increase in the number of consumers (from the time at which supply within the region was commenced or shortly afterwards) and the date on which the premises of each existing consumer was first given supply were known, agreed to furnish the E.R.A. subcommittee with the date of first connection for any premises within these regions indicated to them as having been the seat of a fire attributed by the fire authorities to electrical causes.

The total number of consumers at the end of 1949 in the regions covered was about $2{\cdot}5 \times 10^6$. The individual regions range from areas to districts.

The J.F.R.O. agreed to subdivide their attribution of causes of fires associated with electric wires and cables between defects in fixed wire and cable and defects in flexible wire and cable, and to supply the E.R.A. with the addresses of all premises within the defined regions at which fires attributed to the former cause occurred. This information was supplied on condition that it did not give rise to inquiries at the premises concerned.

Thus initially the Boards provided information on numbers of consumers from which the age distribution of the installations covered could be estimated. Each month the J.F.R.O. provided lists of premises within the specified areas at which fires attributed to defects in fixed wires and cables had occurred. These were circulated to the Area Boards, which then indicated the dates at which supply had first been given at each premises. The Area Boards also generally indicated whether the fire had been reported to the Board and, where an inspection had been made by their officers, provided a copy or abstract of the resulting report.

It is probable that the requirements of the survey imposed a bias towards installations formerly associated with municipal supply undertakings, and thus towards urban premises. For obvious reasons the London area was excluded from the survey.

Collection of data was continued throughout the years 1951, 1952 and 1953.

(3) AGE DISTRIBUTION OF INSTALLATIONS COVERED

Not all the Boards could state the total number of consumers at the end of each year back to the commencement of supply. The data could be divided into three groups going back respectively to 1927, to 1920, and to 1915 or earlier. In about 8% of the cases the data were insufficient for more than a rough check to confirm that they were more or less concordant with the remainder. The number of consumers at the end of each year back to 1927 could be obtained directly by the addition of data for the individual regions. In the earlier years, the proportionate rate of increase each year over the whole sample was taken to be the same as that of the group comprising all regions for which

The paper is based on Report Ref. V/T117 of the British Electrical and Allied Industries Research Association.

Table 1

NUMBER AND YEARLY INCREASE OF CONSUMERS COVERED BY THE SURVEY

(i)	(ii)	(iii)	(iv)	(v)
Year	Number of consumers at end of year		Increase	
	Actual	In terms of 1949	Actual	In terms of 1949
	$\times 10^4$	%	$\times 10^4$	%
1915	18·81	7·3	18·31*	7·3*
1916	19·40	7·6	0·59	0·3
1917	19·78	7·7	0·38	0·1
1918	20·29	7·9	0·51	0·2
1919	22·21	8·7	1·92	0·8
1920	24·44	9·5	2·23	0·8
1921	26·54	10·4	2·10	0·9
1922	29·51	11·5	2·97	1·1
1923	33·07	12·9	3·56	1·4
1924	37·09	14·5	4·02	1·6
1925	42·01	16·4	4·92	1·9
1926	48·21	18·8	6·20	2·4
1927	54·15	21·1	5·94	2·3
1928	63·22	24·7	9·07	3·6
1929	71·96	28·1	8·74	3·4
1930	82·01	32·0	10·05	3·9
1931	94·31	36·8	12·30	4·8
1932	106·02	41·4	11·71	4·6
1933	121·62	47·5	15·60	6·1
1934	137·84	53·8	16·22	6·3
1935	153·37	59·9	15·53	6·1
1936	171·46	66·9	18·09	7·0
1937	187·63	73·3	16·17	6·4
1938	203·36	79·4	15·73	6·1
1939	213·57	83·4	10·21	4·0
1940	212·42	82·9	−1·15	−0·5
1941	214·37	83·7	+1·95	+0·8
1942	215·98	84·3	1·61	0·6
1943	217·67	85·0	1·69	0·7
1944	219·75	85·8	2·08	0·8
1945	223·36	87·2	3·61	1·4
1946	232·09	90·6	8·73	3·4
1947	240·88	94·1	8·79	3·5
1948	248·23	96·9	7·35	2·8
1949	256·11	100·0	7·88	3·1

* Total increase since beginning of supply.

data were available. Table 1 gives, in column (ii), the resultant estimate of the total number of consumers in the area covered by the survey at the end of each year. The increase in the number of consumers between the beginning and end of each year is taken as the number of new installations connected in that year, and thus the number of installations of that year at risk. The date of accounting was not the same in every case, but no correction has been made for this. Column (iv) of Table 1 shows the resultant estimate of the increase in the number of consumers, i.e. approximately the number of new installations, for each year from 1916 onwards, with the number of installations existing at the end of 1915. The information is perhaps more clearly presented in the histogram, Fig. 1.

There are obvious weaknesses in the assumption that the

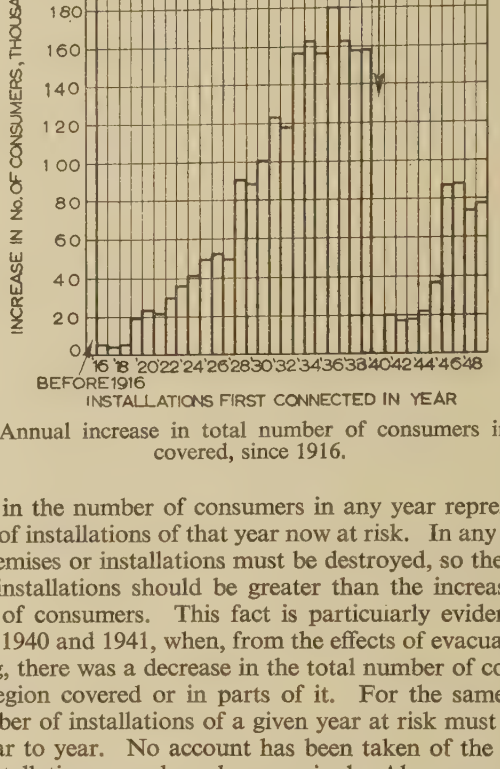


Fig. 1.—Annual increase in total number of consumers in region covered, since 1916.

increase in the number of consumers in any year represents th number of installations of that year now at risk. In any one yea some premises or installations must be destroyed, so the numbe of new installations should be greater than the increase in th number of consumers. This fact is particularly evident in th data for 1940 and 1941, when, from the effects of evacuation an bombing, there was a decrease in the total number of consumer in the region covered or in parts of it. For the same reason the number of installations of a given year at risk must decrea from year to year. No account has been taken of the fact th some installations may have been rewired. Also, some install tions do not strictly belong to a single year, since they have bee extended. Whilst it might be possible to take account of th in estimating the number of installations at risk, it would correspondingly necessary to ascertain whether defects in su installations had arisen in the original or the additional part the installation; this would require much more detailed repor on the individual fires than have been made available. In th present work, all installations in a given premises have, whe possible, been credited to the date of the original installation that premises. In a few cases a date of rewiring only has bee given; these installations have been credited to that year. Th fact that these considerations have been neglected should gi added significance to any correlation with age indicated l the results.

It appears possible to obtain much more precise statistics o all the points noted above, but since a rather elaborate investig tion would be required, incurring inevitable delay, it was desire to carry through the present survey on the simplest possible bas

(4) SCOPE OF INFORMATION RECEIVED

The total number of fires dealt with is indicated in Table for the purposes of which the regions covered have bee divided into seven groups, each including not less than 1000 consumers. In general, a group comprises all the consume contributed by a single Area Board, but one group includes the consumers from two Area Boards and another tho from three.

The survey covered 1 100 fires in the three years. The inciden of fires per 10000 consumers per year varied considerably from 2·44 to 0·36, but the various groups maintained broadly consistent level, with the exception of Group E.

To bring these data into perspective with those relating to t whole country, Table 3 shows the incidence of fires (due

Table 2

FIRES ATTRIBUTED BY FIRE AUTHORITIES TO DEFECTS IN FIXED ELECTRICAL WIRE AND CABLE IN REGIONS COVERED BY SURVEY

Group	Population	Total number of fires in period				Fires in premises connected after 1949				Fires in premises connected before 1950				Fires in premises connected before 1950, per year per 10 000 premises			
		1951	1952	1953	1951–53	1951	1952	1953	1951–53	1951	1952	1953	1951–53	1951	1952	1953	1951–53
	$\times 10^4$																
A	92·5	145	88	104	337	1	2	1	4	144	86	103	333	1·56	0·93	1·11	1·2
B	13·8	14	6	11	31	1	—	1	2	13	6	10	29	0·94	0·47	0·78	0·75
C	55·6	125	93	109	327	2	4	4	10	123	89	105	317	2·21	1·78	1·89	2·9
D	41·2	51	32	36	119	1	4	2	7	50	28	34	112	1·21	0·68	0·82	0·91
E	13·8	31	22	6	59	—	1	—	1	31	21	6	58	2·32	1·52	0·36	1·4
F	25·4	61	37	36	134	3	—	—	3	58	37	36	131	2·28	1·46	1·42	1·72
G	13·9	34	28	31	93	—	1	—	1	34	27	31	92	2·44	2·02	2·23	2·21
Total	256·2	461	306	333	1 100	8	12	8	28	453	294	325	1 072	1·77	1·15	1·27	1·4

Table 3

GENERAL STATISTICS ON INCIDENCE OF FIRES DUE TO DEFECTS IN FIXED WIRE AND CABLES

(i)	(ii)	(iii)	[(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)
Year	England and Wales			Scotland			Northern Ireland		
	Consumers at end of year	Fires during year		Consumers at end of year	Fires during year		Consumers at end of year	Fires during year	
		No.	Per 10 000 consumers		No.	Per 10 000 consumers		No.	Per 10 000 consumers
	$\times 10^6$			$\times 10^6$			$\times 10^6$		
1949	11·53	2 272*	1·97	1·21	368*	3·04	0·22	40*	1·82
1950	11·93	1 694	1·42	1·27	206	1·62	0·23	56	2·43
1951	12·29	2 186	1·78	1·33	270	2·03	0·25	34	1·36
1952	12·65	2 268	1·79	1·38	236	1·71	0·26	68	2·62
1953	13·10	2 270	1·73	1·45	255	1·76	0·27	45	1·67

* Includes an unknown number of fires due to faults in flexible leads to apparatus. In 1950 and 1951 these amounted to 264 and 166.

Table 4

SCOPE OF INFORMATION RECEIVED

Group	Fires at premises with installations of known age				Fires at premises with installations of unknown age				Fires with information									Total fires reported			
									Known age				Unknown age				Total				
	1951	1952	1953	1951 –53	1951	1952	1953	1951 –53	1951	1952	1953	1951 –53	1951	1952	1953	1951 –53	1951 –53	1951	1952	1953	1951 –53
A	88	40	39	167	57	48	65	170	59	28	30	117	31	29	42	102	219	145	88	104	337
B	13	4	8	25	1	2	3	6	7	2	6	15	1	—	1	2	17	14	6	11	31
C	88	92	100	280	37	1	9	47	31	55	73	159	4	—	—	4	163	125	103	109	327
D	39	18	28	85	12	14	8	34	26	12	18	56	2	—	4	6	62	51	32	36	119
E	26	16	6	48	5	6	0	11	74	11	6	41	1	3	—	4	45	31	22	6	59
F	60	36	31	127	1	1	5	7	43	31	23	97	1	—	1	2	99	61	37	36	134
G	29	12	20	61	5	16	11	32	24	8	13	45	1	2	5	8	53	34	28	31	93
Total	343	218	232	793	118	88	101	307	214	147	169	530	41	34	53	128	658	461	306	333	1 100

defects in fixed wire and cable) per 10000 consumers per year, for England and Wales, Scotland, and Northern Ireland, for the years 1949–53 inclusive. The entries in columns (iii), (vi) and (ix) are abstracted from statistical analyses of reports of fires attended by fire-brigades in the United Kingdom. The numbers of fires are derived from random samples of all reports received from fire-brigades. The proportions sampled were 1 in 2 in 1950 and 1951, 1 in 4 in 1949 and 1952, and 1 in 5 in 1953. For this reason undue importance should not be attached to small differences between the entries, especially those for Scotland and Northern Ireland. The sample covered by the survey appears on the whole to have suffered rather more lightly from such fires than the remainder of the country.

Table 4 shows the extent to which the information received

was complete. In the event, it was found possible to determine the dates of connection in only 72% of the cases, figures for the various regions ranging from about 50% to nearly 100%. In 60% of the cases information other than the date was provided, but in only 48% of cases were both date and additional information available. The nature of the additional information varied greatly, ranging from a fairly complete analysis to a mere statement that the fire was due to a fault in the wiring.

(5) VARIATION OF INCIDENCE OF FIRES WITH AGE OF INSTALLATION

Table 5 summarizes the data available on the distribution of fires amongst installations of various ages.

Fig. 2 is a histogram showing how the 793 fires in cases where dates of connection are known are distributed amongst installations of various ages. In this diagram the ordinate at any year

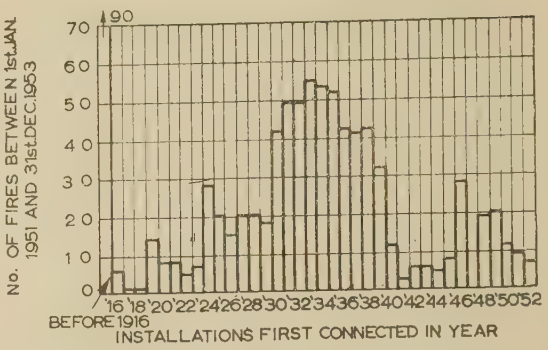


Fig. 2.—Distribution of fires amongst installations of various ages.

Table 5

INCIDENCE OF FIRES DURING 1951, 1952 AND 1953 BY YEAR OF INSTALLATION AFFECTED

Year	Number of installations	Number of fires				Fires per 10 000 installations			
		1951	1952	1953	1951–53	1951	1952	1953	1951–53
	$\times 10^4$								
Before 1916	18·81	50	17	23	90	2·66	0·90	1·22	1·59
1916	0·59	5	0	1	6	8·48	0·00	1·7	3·39
1917	0·38	0	1	0	1	0·00	2·64	0·00	0·88
1918	0·51	0	0	1	1	0·00	0·00	1·96	0·65
1919	1·92	8	1	5	14	4·17	0·52	2·61	2·43
1920	2·23	3	4	1	8	1·34	1·79	0·45	1·19
1921	2·10	2	3	3	8	0·95	1·43	1·43	1·27
1922	2·97	1	2	2	5	0·34	0·67	0·67	0·56
1923	3·56	2	2	3	7	0·56	0·56	0·85	0·69
1924	4·02	10	10	8	28	2·49	2·49	1·99	2·32
1925	4·92	12	4	4	20	2·45	0·81	0·81	1·36
1926	6·30	8	4	3	15	1·27	0·63	0·48	0·79
1927	5·94	14	3	3	20	2·36	0·51	0·51	0·13
1928	9·07	7	10	3	20	0·77	1·10	0·33	0·73
1929	8·74	5	7	6	18	0·57	0·80	0·69	0·69
1930	10·05	13	10	9	32	1·30	0·99	0·89	1·06
1931	12·30	10	10	19	39	0·81	0·81	1·55	1·06
1932	11·71	9	14	16	39	0·77	1·19	1·37	1·11
1933	15·60	19	10	16	45	1·22	1·64	1·03	0·96
1934	16·22	13	14	16	43	0·80	0·86	0·99	0·88
1935	15·53	19	14	9	42	1·22	0·90	0·58	0·90
1936	18·09	15	8	9	32	0·83	0·44	0·50	0·59
1937	16·17	18	8	5	31	1·11	0·50	0·31	0·64
1938	15·73	16	5	11	32	1·02	0·32	0·70	0·68
1939	10·21	7	9	6	22	0·68	0·88	0·59	0·72
1940	−1·15	5	3	4	12	—	—	—	—
1941	1·25	1	1	1	3	—	—	—	—
1942	1·61	4	1	1	6	2·48	0·62	0·62	1·24
1943	1·69	2	3	1	6	1·18	1·78	0·59	1·18
1944	2·08	1	3	1	5	0·48	1·44	0·48	0·80
1945	3·61	6	1	1	8	1·66	0·28	0·28	0·74
1946	8·73	9	9	10	28	1·03	0·13	1·15	1·07
1947	8·79	21	8	11	40	2·4	0·91	1·25	1·52
1948	7·35	10	1	8	19	1·36	0·14	1·09	0·86
1949	7·88	10	6	4	20	1·27	0·76	0·51	0·85
1950	—	4	5	3	12	—	—	—	—
1951	—	4	2	3	9	—	—	—	—
1952	—	—	5	2	7	—	—	—	—
1953	—	—	—	0	0	—	—	—	—

indicates the total number of fires occurring between 1st January, 1951, and 31st December, 1953, in the installations of that year within the sample. This information by itself is not of much significance.

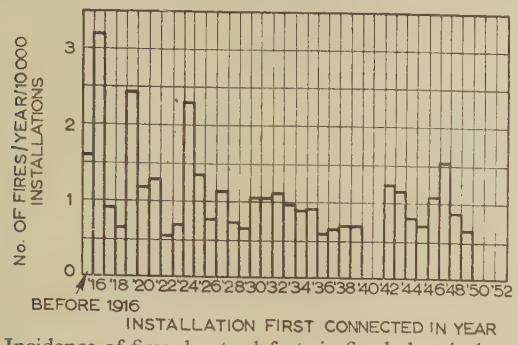


Fig. 3.—Incidence of fires due to defects in fixed electrical equipment: variation with age of installation.

Fig. 3 shows how the incidence of fires varied between the installations of different dates. The incidence over the years 1951–53 for any one age-group is obtained by dividing the total number of fires corresponding to the particular age-group by three times the number of installations in that group. Thus the ordinate at each year indicates one third of the number of fires occurring between 1st January, 1951, and 31st December, 1953, per 10000 installations of that year. This is the information which the survey was primarily designed to provide. Installations of the years 1940 and 1941 are left out of consideration because of the uncertainty noted above on the number of installations of these years at risk.

There is a very strong indication that for installations connected before 1939 the incidence of fires is increasing with the age of installations; there is now a greater chance that an installation connected in, say, 1925 will cause a fire in 1956 than that an installation connected in, say, 1938 will do so. The incidence for the relatively large class of pre-1916 installations appears surprisingly low, but this may well be due to a substantial overestimate of the number at risk, by reason of the relatively large number of pre-1916 installations probably abandoned or completely rewired since that year.

The fire incidence for installations of the post-war years at first seems surprisingly high. It is common knowledge, however, that the use in these years of new techniques in building construction and in installation practice introduced a number of new causes of fires. This is fully confirmed by the detailed information analysed below.

It thus seems appropriate to consider the period 1916–39 as one in which installation and building practice were stable, or at least developing uniformly, and to examine separately the experience with installations of these years. Marked on Fig. 4

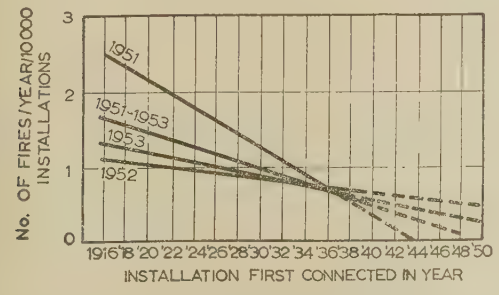


Fig. 4.—Variation of incidence of fires with age, for years 1951, 1952 and 1953 separately.

The lines plotted are those of best fit through the data for each year.

are the straight lines of best fit for the data corresponding to Fig. 3 on installations connected between 1916 and 1939, for the years 1951, 1952 and 1953, taken separately and for the whole period 1951–53. In each case the incidence of fires increases with the age of the installation, and indeed the data for the whole period suggest that during that period the risk of fire in any installation was directly proportional to its age measured from 1951. It may be concluded that there is definite evidence that the older installations are more subject to fires than are the new, and indeed the data appear to indicate that the chance that a fire will occur in a given installation in a given year is about seven in a million for each year of its age.

(6) RELIABILITY OF ATTRIBUTION

In 658 out of the 1100 cases reported, information on the cause of the fire was available from reports made by the local supply authority. In 57 of these the attribution to electrical causes was disputed. Some such cases arising in 1951 were reviewed and it was found that one or two were motor-car fires included by an error in sorting; it is possible that a few similar cases arose in the following years. It is by no means to be assumed that attribution to electrical causes is definitely wrong in the remainder of the 57 disputed cases. In a smaller number of cases the electrical authorities suggested that the evidence was really insufficient to support definite attribution to electrical causes. Allowing that the fire authorities were correct in these, it appears that the assessment of electrical causes was correct in at least 601 cases, or roughly 90% of all those on which information is available. The distribution of disputed cases by groups and by years is given in Table 6.

Table 6

FIRES WITH ELECTRICAL ORIGIN DISPUTED BY ELECTRICAL AUTHORITIES

Group	Year			
	1951	1952	1953	1951–53
A	5	9	9	23
B	—	—	1	1
C	6	2	3	11
D	1	1	1	3
E	—	—	—	—
F	7	4	2	13
G	3	1	2	6
Total	22	17	18	57

All the 601 fires were attributed to defects in the fixed parts of the electrical installations. In the first year there were included 7 attributed by the electrical authorities to defects in radio sets and their flexible cords. Again error had arisen in sorting; fewer occurred in later years. A few cases were of fires due to overheating of motors. It was not intended that these should be included, but the equipment was usually commercial, and thus, since it was possibly not connected through a socket outlet, legitimately regarded as fixed. Equally, a few fires due to defects in flexibles without a secondary cause in fixed wiring were included, but most of them legitimately, since the flexible cords were directly connected to the fixed installation (e.g. a pear switch connected to a ceiling rose) or were regarded as permanent (fixed to walls by staples, or laid under carpets). Although it is difficult to be precise on the matter it can be said that the attribution in this respect was correct in a very high percentage of cases.

Some of the occurrences are complex, and there are naturally a number of borderline cases.

It is to be remembered that what is classed as a fire is an event giving rise to a call to the fire-brigade. Many such are quite trivial, and a few are not fires in any real sense of the word, but no analysis is possible on a basis of severity.

(7) PARTICULAR SOURCES AND CAUSES OF FIRE

Table 7 summarizes the detailed information provided. It has often been possible to distinguish either the class of equipment in which the defect causing a fire arose, or the class of defect, and in a few cases both. Satisfactory analysis is difficult because one, two or even more defects may contribute to a single fire. Examples of a single cause are a loose connection or a defect in insulation which draws enough energy to start a fire before it causes a fuse to blow. Such causes only enter properly into the present survey if they arise in fixed wiring or fittings. Two defects may combine, as when there is defective insulation to earth with an earth-continuity conductor touching a composition gas-pipe, but otherwise adequately earthed by normal standards. Both defects are discussed below. Where in such a case the earthing is also inadequate three defects combine. The total number of defects discussed is thus considerably greater than the total number of cases on which there is information.

Table 7

SUMMARY OF INFORMATION ON ORIGIN OF FIRES ATTRIBUTED TO ELECTRICAL CAUSES

Cause	Total	Number without dates
Reported electrical but disputed ..	57	—
Defects in service equipment	82	27
Defects in fittings	121	22
Defects in wiring	264	23
Loose connections	44	10
Unauthorized wiring, etc.	54	10
Moisture	46	30
Heat	7	1
Defects in appliances	74	13
Earth faults associated with gas ..	188	18
Earth faults not associated with gas ..	27	1

(7.1) Defects in Service Equipment

The section of the investigation most easily handled, because most complete information is available, is that relating to equipment owned by Area Boards. The Boards will naturally be aware of all fires due to defects in their own property. Of the whole set of 1 100 fires reported, 82 were due to defects in service equipment. Although low, the proportion is perhaps greater than might have been expected, but it is to be remembered that a defect in service equipment is much more likely to cause a fire than is a defect in consumer's equipment, because the protection will be less sensitive, and load and fault currents higher.

Table 8 summarizes what information is available. The most common cause of fires is the fuse. In the great majority of cases the fire was due to direct generation of heat at the fault and in only a few to ignition of gas at a punctured composition gas-pipe. One case worth special note illustrates a risk which supply authorities accept when allowing the use of the service cable sheath as an earth connection. The report in this case is as follows:

"The lead sheath on the mains cable in the road burnt through due to a fault at a service box and became 'live.' Due to the fact that the lead sheath became open circuited from the earth system the fault current passed through the consumer's earth wire to a gas-pipe. The consumer's installation was earthed to the lead sheath of the service cable. Apart from damage to consumer's wiring, no actual damage occurred."

There are insufficient data for satisfactory examination of the effects of age on this class. Some influences are shown by the diagrams of accumulated totals in Fig. 5, on which, to a base of age in years, are plotted (*a*) the percentage of all installations less than the indicated age at the end of 1949, and (*b*) the percentage of all fires which were in installations of less than the indicated age. The incidence of fires appears fairly uniform over all ages except that it is rather high in installations between 15 and 21 years old, where 30% of the installations in this class suffered 43% of all fires, and in installations more than 33 years old, where 7½% of all installations suffered 15% of all the fires. The former observation might be explained if, for example, connection of d.c. services on any considerable scale had ceased after 1928 and if a considerable proportion of those already connected had been changed over in the intervening period.

Table 8

ORIGIN AND TYPE OF DEFECTS IN SERVICE EQUIPMENT

Type of equipment	Number of fires caused			Total	Defects					
					Loose contact	Leakage			Moisture	Gas
	1951	1952	1953			To earth	Between lines	Unspecified		
Fuse	6	14	6	26	5	1	—	7	5	—
Service cable	7	5	5	17	—	—	1	14	3	—
Meter	5	3	5	13	1	3	—	10	3	2
Service tee-joint	—	—	2	2	—	—	—	2	—	1
Sealing chamber	3	1	1	5	3	—	1	2	2	—
Service intake (overhead) ..	1	—	1	2	—	—	1	3	—	—
Service wiring	2	—	9	11	—	—	—	10	2	2
Other	1	1	4	6	—	—	—	2	2	—
Total	25	24	33	82	9	4	3	50	17	5

(7.2) Defects in Fittings

Of the 537 fires on which there is sufficient information

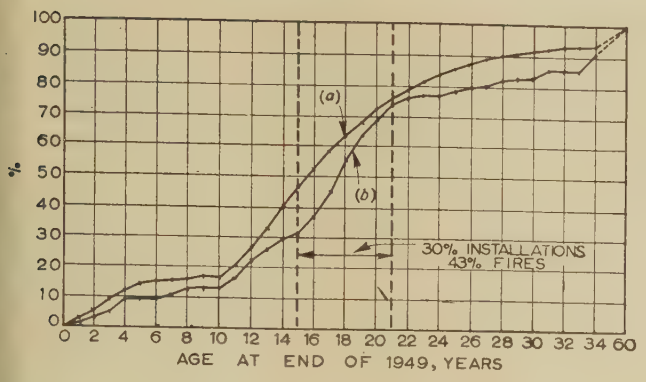


Fig. 5.—Age distribution of fires due to defects in service equipment.
(*a*) Number of installations of age less than abscissa, expressed as percentage of all installations.
(*b*) Number of fires occurring in installations of age less than abscissa, expressed as percentage of all fires.

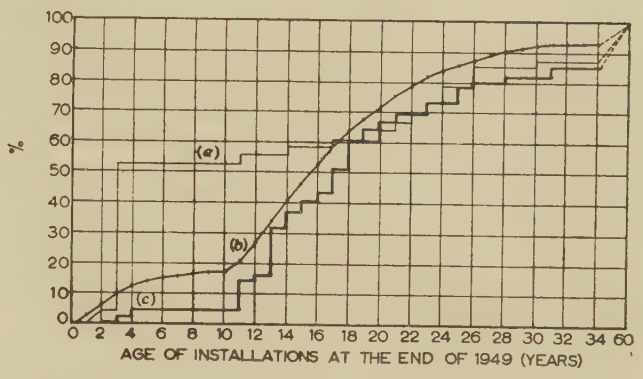


Fig. 6.—Age distribution of fires due to defects in fittings.
(*a*) Fires due to defects in fuses, fuseboards, distribution boards, control panels, etc.
(*b*) Percentage of all installations.
(*c*) Fires due to defects in fittings other than fuseboards, etc.

enable the originating defect to be determined, 100 were due to defects in fittings other than those of the service at the premises. The term fittings naturally covers the wiring terminations associated with the fittings. Table 9 gives analysis of these 100 fires by class of fitting and type of defect, where known.

including flexible cords from ceiling roses, etc. It is not at all clear how these defects were divided between the wiring proper and the terminations. Table 10 gives an analysis by types of wiring in which the defects arose, and the analysis might be useful were information available on the relative frequency of occurrence of the types.

Table 9

DEFECTS IN FITTINGS

Type of fitting	Nature of defect							Totals			
	Loose contact	Leakage			Fuse operation	Moisture	Unknown	1951	1952	1953	Total
		To earth	Between lines	Unspecified							
Earth-leakage circuit-breaker ..							1		1		1
Splitter	1		1	1				2	0	1	3
Switch	4	4	1				4	6	4	3	13
Joint box		1	1	1		1	4	4	2	1	7
Lighting fitting	1	1	1			1	5	2	2	4	8
Ceiling rose	1	1	4			1	1	2	3	2	7
Plug, socket	3	5	2	3			1	9	3	2	14
Fuse, fuseboard, distribution board, control unit, etc.	17	1	1	6	5	2	19	14	17	16	47

The large number of fires (47) due to defects in the class embracing fuseboards, distribution boards, control panels and consumer's units, attracts attention, as also does the large number of cases in this class due to bad contact. The age distribution of this group is of some interest. Fig. 6 displays separately the data for fuseboards, etc., fittings other than fuseboards, and all installations. 50% of all fuseboard fires occurred in the 12% of installations connected after the end of 1945. This of course mainly reflects the well-known fact that in the immediate post-war period, the tendency to substitute moulded plastics fuse carriers for ceramic ones led to some injudicious designs, and the increasing adoption of cartridge fuses sometimes gave rise to abuse by consumers in the form of makeshift replacements.

The data for fittings other than fuseboards suggest a slight deterioration with age and no bad experience from post-war equipment; the 18% of installations less than 10 years old have suffered only 3% of fires.

(7.3) Defects in Fixed Wiring

In 210 fires out of the 537 in which judgment appeared possible, it seems probable that the primary cause was a defect in the fixed wiring, excluding temporary and unauthorized wiring, but

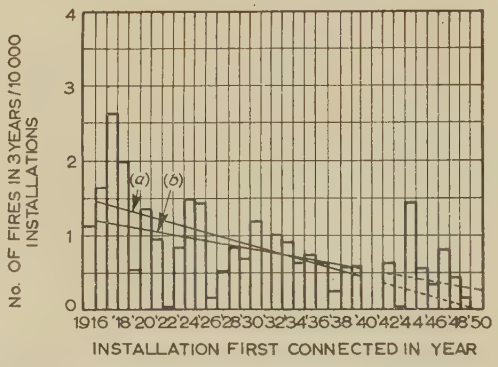


Fig. 7.—Incidence of fires due to wiring defects: variation with age of installation.
(*a*) Line of best fit, 1916–1939 inclusive.
(*b*) Weighted line of best fit, 1916–1939 inclusive.

Fig. 7 is a histogram showing the variation, with age, of the incidence of fires with defective wiring as the primary or only cause. Plotted on this histogram (*a*) is the mean line of best fit

Table 10

FIRES ASSOCIATED WITH DEFECTIVE WIRING ANALYSED BY TYPE OF WIRING

Group	Casing and capping	V.R. l.c.	T.R.S.	V.R. bare	V.R. in conduit	L.C. and conduit	T.R.S. and conduit	L.C. and t.r.s.	Casing and capping and other	Mixed and various	Unknown	Flex	Total
A	1	17	4	2	18	1	0	2	2*	4	12	1	64
B	0	1	0	1	0	1	0	0	0	0	2	0	5
C	2	7	18	0	19	6	6	6	0	3	6	0	73
D	0	2	1	0	6	2	1	0	0	0	5	1	18
E	0	1	0	0	10	1	0	0	0	0	6	1	19
F	0	6	0	0	2	0	0	0	0	0	12	1	21
G	0	4	0	0	1	0	0	0	0	1	4	0	10
Total ..	3	38	23	3	56	11	7	8	2	8	47	4	210

* One l.c.; one in conduit.

for the period 1916–39 inclusive. As with installations in general, this line indicates that the risk of a fire due to defective wiring increases with the age of the installation. Considered in relation to the data for post-war installations, it would suggest also that, as with installations in general, post-war wiring perhaps gives rise to more trouble than would be expected from experience with older installations. To give a second view, curve (*b*), also plotted on Fig. 7, is the mean line of best fit weighted according to the frequency with which observation is possible, i.e. to the size of the sample in each year. This indicates a slightly less rapid increase of incidence with age, and gives a much less marked suggestion that post-war installations differ from pre-war ones. It is possible, of course, that an apparently high incidence of fires in new installations is due to the fact that a certain number of gross faults always occur during erection, and cause fires in the early years of installation life.

A few of the defects in wiring were directly due to lack of mechanical protection—nails through t.r.s. cable, lead sheathing fractured by pressure of floor-boards, bare v.r.-insulated service wiring fractured by the accidental dropping of a heavy object in the meter cupboard. Heat and damp are separately considered below. All the defects in fixed wiring appear, as might be expected, to be due to leakage: 25 of them appear to have been due to leakage between conductors, and 91 to leakage to earth; in the remaining cases judgment is not possible.

(7.4) Unauthorized, Temporary and Amateur Wiring

Out of the 537 fires in which judgment was possible, 54 were due to defects in wiring which was stated to be unauthorized, temporary, or amateur. This includes a number of cases where extensions in flex or v.r.-insulated cable were secured to composition gas-pipes. The older installations might have been expected to give rise to more than their fair share of such fires, but the contrary is in fact the case; 23% of all fires from this cause in the 1916–49 sample occurred amongst the 17% of consumers, connected between the end of 1940 and the end of 1949, and two cases were noted in installations first connected in 1950.

One or two fires due to amateur wiring originated in faulty joints.

(7.5) Fires due to Defects in Appliances

Of the fires reported 75 are known to have arisen primarily from defects in appliances or flexible cords beyond socket outlets. Of these, 14 were due to radio sets or radio-set cords, probably included by an error in sorting. Of the remaining 61, 36 were due to contact between a gas-pipe and either an earth-continuity conductor carrying the earth-fault current from the defect in a portable appliance or its flexible cord, or a girder or water pipe, with which a faulty unearthed appliance was in contact. Nine fires were due to overheating of motors, probably fixed, four to defects in immersion heaters, two to defects in battery-charging equipment, and four to ignition of foodstuffs or other material by cookers. A cooker to which no thermostat is fitted can, however, hardly be called defective if it causes fire by overheating when the oven is inadvertently left switched to full heat. The remaining six cases probably originated solely from defects in or abuse of portable equipment, with no secondary cause in the fixed installation, and were thus wrongly classified.

(7.6) Leakage to Gas-Pipes

Of the 658 fires on which there is information, 185 were in some way associated with gas, and nearly all arose from the passage of earth-fault current to a gas-pipe and the consequent ignition of gas. A few were due to the ignition of pockets of gas from leaky gas-pipes by arcing or sparking at a fault, and one or two to the ignition of a gas leak by the correct operation of a fuse. In cases where the fire was associated with the passage of earth-fault current, no purpose seems to be served by studying the primary cause. Again, in the majority of fires, the passage of fault current was from an earth-continuity conductor to a gas-pipe, but a number were due to direct passage of current from faulty unearthed appliances or from defective flex or v.r. wiring (usually but not always unauthorized extensions), to composition gas-pipes which they were touching or to which they had been secured.

Data relating to fires caused by gas are given in Table 11. Noteworthy is the number of cases in which the current passed from the faulty appliance to the gas-pipe by a third conductor, usually a water-pipe or structural steelwork. Undetermined cases include those where gas is suspected but all evidence has been removed, those where gas-pipes clear of wiring or earth-continuity conductor or other metal work melted without obvious cause, and those where fires were due to contact between radio earths and gas-pipes, and bell wiring and gas-pipes. There are one or two curious cases, such as a fire in 1951 in which the screw of a hook securing new composition gas-piping penetrated the covering of a t.r.s. wire and one in which a screw securing a pendant, which must have been faulty, penetrated a composition gas-pipe.

In a number of cases the adequacy of the earthing provision was tested after the fire. It should be mentioned that fires can frequently be caused by the passage of fault current from an earth-continuity conductor to a gas-pipe even when the earthing provisions are satisfactory in that they permit the rapid operation of a fuse on the occasion of a fault to the earth-continuity conductor.

Table 11

DETAILED CAUSES OF FIRES ASSOCIATED WITH LEAKAGE TO GAS PIPES

	1951	1952	1953	Total
Leakage to earth-continuity conductor	61	35	37	133
Wiring touched gas-pipe ..	10	3	2	15
Fuse blowing ignited gas leak	—	2	—	2
Other or undetermined ..	8	16	11	35
Total	79	56	50	185

Current carried to gas-pipe by water-pipe, girder, etc.* ..	25
Contact between earth-continuity conductor and gas-pipe of a fortuitous nature	119
Conduit or L.C.C. cable stated to be unearthed	22
Earthing stated to be inadequate	31
Earthing lead broken or disconnected during repairs, earthing otherwise satisfactory	5
Earthing stated and strongly presumed to be satisfactory, in cases where leakage was to earth-continuity conductor	9

* Either from earth-continuity conductor or from faulty unearthed appliance touching range, water-pipe, girder, etc.

In a large number of instances it has been possible to assess the nature of the contact between earth-continuity conductor and gas-pipe. In nearly all, the connection is described as "touched," "in contact with" or "sparked" and the strong presumption is that the puncture of the gas-pipe (and the origin of the fire) was at the point of fortuitous contact. There appears, however, to be a few cases in which the contact between the systems was robust, and the gas-pipe melted elsewhere. One instance is noted of a fire due to contact between an earth-continuity conductor and an iron gas-pipe.

It is useful to study the relation between fires due to gas and the age of installations, for a purely negative reason. Since fires associated with gas form a large proportion of the total, it might be suspected that apparent ageing indicated by the data as a whole is due to the greater possibility in older premises of the co-existence of electric installations and composition gas systems. If this were so the incidence of fires due to gas should show a

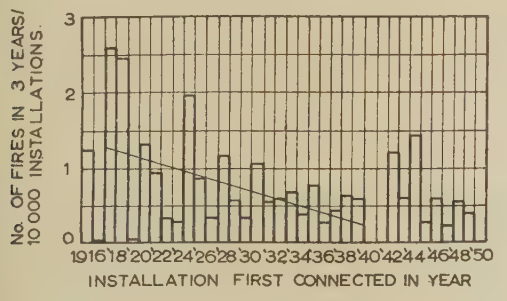


Fig. 8.—Incidence of fires due to electrical ignition of gas: variation with age of installation.
Line of best fit, 1916–1939 is shown.

marked increase with age. In fact the variation (see Fig. 8) is little, if any, greater than that for fires due to wiring defects, and less than that for fires as a whole.

(7.7) Leakage due to Moisture or Heat

It seems likely that at least 400 of the fires were started by leakage current, and in 46 cases the leakage was attributed to moisture, mainly the damp condition of buildings, although there are a number of cases in which large quantities of water were involved, as by overflow of cisterns or burst pipes. The wiring was affected in 23 instances, fittings in 5 instances and service equipment in 17. The high proportion associated with service equipment possibly has some connection with the more thorough investigation likely in such cases. Included in the reports received were 20 on fires due to the inundations of 1953, but these are completely excluded from the survey except for their mention here.

There were 7 cases where leakage was attributed to heat, usually where wires were taken through hot cupboards, or where heat-resisting cable was not used for connection to immersion heaters in lagged tanks. One or two additional cases were due to overloading of wiring, but these were remarkably few.

(7.8) Defective Earthing

All ignitions of gas from punctured or melted gas-pipes must in some way have been associated with faults to earth, and it is possible to determine that 133 of these were faults to an earth-continuity conductor. There are only 27 other cases in which a fire was definitely associable with leakage to an earth-continuity conductor or a metal sheath round conductors. Of these 27, there were three instances in which fire was caused by arcing at a defective bond in an earth-continuity conductor, and earthing was stated to be defective in a further eight instances, but it does not appear that it was so in the other 16.

A similar situation arises with the fires attributed to gas. Table 11 shows that in nine of the 133 cases in which leakage was to an earth-continuity conductor the earthing was stated to be satisfactory, as against 58 in which it was stated to be defective. But the reports as a whole leave the impression (e.g. by the absence, where repairs are described, of references to rectification of earthing) that a large number of earth faults cause fires, even those involving gas, when the earthing provisions, except in relation to separation from other services, comply with wiring regulations. This impression was very strongly conveyed by reports from one particular district, and the point was raised with the authorities. The reply confirmed that in an area where the resistance to the general mass of the earth from the main earthing terminal is usually of the order of 0·75 ohm, tests carried out very shortly after such fires have resulted in a reading of 1 ohm or less for the resistance of the earth-continuity conductor between a point on the cable sheathing or conduit and the main earthing terminal.

(7.9) Loose Contacts

Forty-four fires were caused by loose contacts or connections. Of these nine were in service equipment, three in unauthorized wiring, and the remainder in fittings. Study of age distribution is not profitable because a considerable proportion of the last-mentioned group was associated with fuseboards and distribution boards, which are seriously affected by the post-war changes in practice referred to in Section 7.2.

(8) DISCUSSION

As regards the ageing of installations, the survey described does little beyond confirming the views of those with experience in the matter. On the present data there does appear to be a significant increase in the incidence of fires with age of installations, but no indication of any significant departure from the linear rate. A more elaborate statistical attack is possible and could yield useful results, but this would preferably be based on a more accurate estimate than that available at present of the number of installations in each age group. With this, with

information on rewiring, and with an allocation of causes of fire as between the original and subsequent portions of installations which had been extended, very significant information could be obtained. It is possible that with some preliminary organization, the appropriate authorities could with little effort maintain a survey of this kind continuously in operation. It is important to determine whether there is an age at which risks begin to increase rapidly, since, if there is, a very large increase in the number of fires may be expected when the large numbers of installations of the 1930's reach that age.

The detailed information here presented is a by-product. As in the main investigation, there is probably little that does more than confirm present expert opinions. No single type of defect shows a particularly rapid increase with age. A stronger association might have been expected between fires and earthing which is defective because of excessive impedance. The fact that a large number of fires were due to leakage to composition gas-pipes was well known; it is perhaps surprising that so many such fires occur where the earthing is satisfactory except with respect to contact with gas-pipes. The large number of fires in which the damage was caused by a fortuitous contact probably of small current-carrying capacity raises again the question whether bonding might not be a more satisfactory solution than attempts at separation. There are, of course, a few cases where gas-pipes appear to have melted at a point remote from any contact with electrical requipment.

The relatively large number of fires in service equipment probably indicates mainly the importance of sensitive protective equipment.

The distribution of instances of defective wiring as between authorized (210) and unauthorized (54), calls for some comment, since it seems unlikely that 20% of all wiring falls in the unauthorized class. Thus, although at present unauthorized or amateur wiring does not seriously increase the overall incidence of fires, it must considerably increase the risk in those premises in which it exists.

The information does bring out the very large number of types of equipment and of defects which can give rise to fire, and apart from gas-piping, there is no single one to which attack could be directed with the hope of an outstanding reduction in the number of fires.

(9) CONCLUSIONS

From this survey of the incidence of fires amongst about 2·5 million consumers, mostly in urban areas, over the years 1951–53, the following conclusions may be drawn:

(*a*) Information is available and is being regularly produced which is likely, on complete analysis, to yield significant information on the ageing of electrical installations.

(*b*) From the present rather crude analysis, it is evident that for installations in existence at the end of 1939 there is a direct relation between fires due to defects in fixed electrical equipment and the age of installation.

(*c*) There is no clear evidence of any rapid increase in incidence of fires after any specific age limit is passed. The data at present available are insufficient to support a detailed examination of this point.

(*d*) The incidence of fires in installations more than ten years old is approximately proportional to age; the chance that an installation will be subject to fire in a given year is about 7 in a million for each year of its age in that year.

(*e*) No one of the separate classes of defect which may cause a fire shows the effects of ageing to a more marked extent than any other.

(*f*) Post-war installations have a fire risk greater than would be expected from the experience with pre-war installations. This is because of the unduly large number of fires associated with fuses, fuseboards, distribution boards, control units and the like probably mainly of early post-war design.

(*g*) Contact between an earth-continuity conductor and composition gas-pipe is the most common secondary cause of fire. In a large proportion of such cases, the contact is of fortuitous nature and the gas-pipe is punctured at the point of contact. There appear to be few cases in which gas-piping melted remote from a point of sound contact.

(*h*) Fires due to contact with gas-pipes occur even when earthing is satisfactory in all respects except that of separation from other services.

(*j*) In 25% of the fires due to leakage in service equipment the leakage was definitely attributed to moisture.

(*k*) A number of separate causes of fire are discussed in the body of the report.

(10) ACKNOWLEDGMENTS

The British Electrical and Allied Industries Research Association is indebted to the Joint Fire Research Organization and to many Area Electricity Boards, for the supply of the information on which the paper is based. The author is indebted to his colleague, Mr. W. Makowski, for assistance in the analysis of the detailed information on causes of fires, and to the Director of the British Electrical and Allied Industries Research Association for permission to publish the paper.

DISCUSSION BEFORE THE UTILIZATION SECTION, 19TH JANUARY, 1956

Mr. S. J. Emerson: The statistical evidence in the paper indicates that there is a general increase in danger for installations over 10 years old, but the rate of increase, as disclosed by records of fires, does not seem to be alarming. I believe that the majority of installations in this country which were properly installed 10 years ago are in sound condition to-day. The author implies that insulation deterioration is liable to take place after about 10–15 years, but I believe that 25–30 years would probably be a more accurate estimation, although we have little evidence to support even this.

An example of what can happen with an old neglected installation (40–50 years old) occurred just after the war at a factory in the south of England, when a grain wharf was completely gutted by fire. Examination of a part of the installation undamaged by the fire revealed that vulcanized-rubber cables, protected in screwed tubing, had become brittle by age, and had so badly cracked that the insulation, when stripped of its perished outer covering of cambric and cotton, resembled beads.

The works had been closed down for the summer holiday during which time it had rained consistently; the atmosphere was very damp, and it is a reasonable assumption that the insulation resistance in these conditions was low and that leakage current was the cause of ignition. The dangers attendant on insulation deterioration and consequent earth leakage were demonstrated by means of a h.v. ionization test set and a short length of the conduit and v.r. cable recovered from the wood after the fire.

A number of similar fires have occurred in the past 25 years in large mansions in various parts of the country, the cause being the gradual deterioration of insulation, particularly at terminations at distribution fuse boards, ceiling roses, etc., and at joints in the cables. The solution is not necessarily stripping out

the old wiring, much of which is as sound to-day as the day it was installed, but by carrying out a systematic examination combined with a measurement of the earth leakage; this having been ascertained, steps can then be taken to effect an overall improvement. A switch well suited to both factory and domestic installations, which incorporates differential-current (core-balance) earth-leakage protection with all its advantages in safeguarding from electric shock and risk of fire, is now readily available.

The statistical evidence in the paper does not indicate very clearly just what factors contribute to the fire risk in fixed installations, and I should like the author's views on this.

During the post-war years approximately 1 000 electrical fires have been investigated by the Factory Department, and of these only five were definitely found to be due to deterioration of insulation in old installations. My own experience is that the probable cause of fires with the older installations (over 40 years of age) in factories is deterioration of insulation, conduit and other protection of cables, particularly at terminations. Considering installations as a whole, both factory and domestic, the Factory Department records reveal that the fires are caused by badly damaged distribution boards, badly designed plugs and sockets, leakage to gas pipes, flexible cables and the addition of unauthorized extensions to installations by unskilled persons; perhaps the greatest number of these have been caused by workshop flex, twisted cotton-covered flex, so-called non-kinkable flex and asbestos-braided vulcanized-rubber-insulated flex. The more general use of tough-rubber-insulated circular flex in recent years has greatly reduced the fire hazard.

I think that the great preponderance of fires in comparatively new installations, as disclosed by the statistics in the paper, can largely be attributed to the use of unsuitable cheap flexible cables and the low standard of workmanship just after the war.

In Section 8 the author refers to the relatively large number of fires in service equipment. From the statistics in the paper he is correct, but it is perhaps significant that in the past 20 years less than 100 fires in factories can be attributed to incoming service cable failures.

Mr. P. M. Hollingsworth: It is notable that the survey has singled out some technical faults, such as defects in modern fuse-boards, but for cables there is no indication of inferiority of any one system, and certainly no evidence of approaching catastrophe.

Regarding individual characteristics of cable types, services are mainly paper-insulated metal-sheathed cables, the durability of which is traditional, indicating a life equivalent to that of the building. (Incidentally, while the author mentions domestic premises, he does not specifically exclude churches and other public buildings, or factories or business premises. Perhaps he will explain the scope of the paper in that respect.)

Rubber-insulated cables constitute the bulk of the wiring types, and it is recognized that rubber compounds used prior to the 1930's, which did not contain anti-oxidants, are liable to perish and produce the effects to which Mr. Emerson referred. In the perished condition they are naturally much more susceptible to moisture or movement and therefore present hazards depending on quality of installation and condition of building. With modern compounds the durability of rubber-insulated cable has improved immeasurably, and durability is also a feature of plastic types of insulation such as p.v.c., and still more of the mineral-insulated cable. Some of these materials are fire resistant in themselves, but this is of secondary importance to electrical quality and mechanical strength, and to the workmanship in the installation itself.

The conduit system is probably still the most popular, using both p.v.c. and rubber cables. Cables with copper or aluminium sheaths are gaining popularity for applications other than domestic, but the usage of lead-covered cable has declined; it is readily damaged and liable to sparking. The all-insulated system is free from risk of sparking but vulnerable to damage.

There are one or two points in the paper which require clarification. Table 2 is stated to refer to a total of 1 100 fires attributed to defects in fixed electrical wire and cable. This is misleading, because Table 4 shows that the figure of 1 100 covers all electrical sources, and only in 658 was there specific information. Later in the paper the figure of 537 is referred to, and I gather that this is obtained by taking only those fires on which there is sufficient information to enable the originating defect to be determined; finally the author arrives at a figure of 210 fires attributable to fixed wiring and cables. On the basis that 10% of all fires are attributable to electrical causes, the data show that 2–3% of all fires are due to defects in fixed wiring, with perhaps less than half attributable to deterioration.

With the advent during the past 20 years of improved insulants, deterioration as a factor in fire incidence seems likely to be even less important.

Mr. R. A. Marryat: In considering this paper we should not overlook the fact that there has been a very considerable development in the scope of electrical installations since 1916. At that time the average installation was intended primarily for electric lighting; consequently the very early installations may not be quite so good as they would appear to be in the paper.

It is interesting to note that, where distinction was possible, earth leakage caused 3½ times as many fires as leakage between conductors. The author says that in only two cases were fires caused through overloading of conductors, but it may be that the cause of the earth leakage was deterioration of conductors due to overloading. Undoubtedly the earth-leakage troubles could be prevented by use of core-balance trips, and these would also take account of breaks in the neutral conductor which are so often associated with earth faults on the neutral.

It is stated that 25% of the fires about which there is relevant information were caused by leakage to gas pipes, although in most of these the earthing was found to be satisfactory. In Section 7.8 the author refers to the consumers' earth resistance, but we must also consider the impedance of the supply sub-station electrode if we are to get all the relevant information. If this research is to be continued—as I hope that it will be—it would seem useful to take earth loop tests wherever possible after a fire has occurred.

The paper indicates the need for careful segregation of the electrical services from gas services, but in practice this is not always easy. There are certain appliances on the market which combine electric motive power with gas heating; moreover, cases have been reported where, after completion of the electrical installation, the gas undertaking has installed gas pipes in contact with electrical conduits. The Institution's Regulations for the Electrical Equipment of Buildings now permit bonding the two together, and it would be interesting to know whether any fires have occurred in installations where gas pipes are solidly bonded to the electrical conduits.

I should be surprised if in many of the cases where the cause of a fire was unknown the reason was not the deterioration of flexible cords, especially in premises where there was not an adequate number of socket-outlets. The introduction of the ring circuit was, of course, intended to make it possible to provide a far greater number of socket-outlets in private dwelling houses without greatly increased expense. I should like to see some effort made to compare the statistics of fires occurring in housing estates where the ring circuit has been generally adopted with those in estates built before the introduction of the ring-circuit regulations.

Mr. H. W. Swann: The paper establishes beyond reasonable doubt that there is a relation between fire risk and age and that there may be a critical age.

Apart from the actuarial increase in fire risk and the cost to the community, if a really important installation were to give trouble and cause the destruction of a building such as Buckingham Palace or the headquarters of the T.U.C., an official inquiry might be set on foot which the electrical industry might find embarrassing.

It is pleasing to note that there has been close co-operation between the E.R.A. and the Joint Fire Research Station. I hope that this will continue, because the latter is likely to be in a position to undertake more research on electrical fire causation during the next year.

A number of technical institutions are training many people to take an interest in electrical work as a profession or to use electrical wiring and appliances in the course of their education for other technical activities. These people will naturally apply their knowledge, and if they can make a circuit work and produce light, drive a small motor or heat a water tank there is a great temptation to them to do it, especially at present-day costs of employing 'competent and authorized persons'.

Mr. D. I. Lawson: Within the next two decades we shall be relying increasingly on electrical power, owing to the depreciation of our solid fuel resources. It is expected that over the next 20 years the electrical energy transmitted annually will be trebled, and this will undoubtedly mean an increase in the number of electrical fires.

Fig. A relates the number of fires to the electrical energy

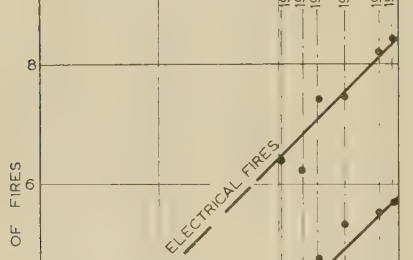


Fig. A

transmitted annually. It will be seen that over the period 1947–52 the number of fires attributed to electrical causes and attended by the fire brigades has increased uniformly with the electrical energy transmitted per annum; the points for 1953 and 1954 are known to lie on the same straight line. The figure for total electrical fires is made up of fires due to wire and cable and fires due to electrical apparatus.

Wire and cable fires, so far as can be seen, are fairly independent of the amount of electrical energy transmitted, and this would support the author's contention that most of the fires are due to leakage rather than to the overloading of electric cables. Fires due to electrical apparatus, on the other hand, are proportional to the electrical energy transmitted and amount to one fire for every 10^6 kWh. From this cause alone the number of electrical fires during the next 20 years might be expected to be trebled, reaching a figure of 18 000 per annum.

The author has made the point that the susceptibility to fire is due to the age of the installation, so that the problem is best considered in terms of the number of installations and the number of years for which they have been in service. At present the circuits in use appear to have an aggregate age of 280 000 000 installation-years, so that by 1975, unless a large amount of replacement takes place, this figure will have increased to 520 000 000 installation-years. This would mean that the fires due to wire and cable at present in service might be expected to nearly double the present figure of 2400 per annum.

These figures are disturbing, and undoubtedly the first measure must be to find out more about the causes of these fires. The accumulation of such information and the devising of effective counter-measures will take time. The present survey is a very good beginning to this work, which I am sure everyone will be glad to see extended in the future.

Mr. N. C. Strother Smith: There are factors other than age which play their part and may have done so in the figures which have been produced. It is quite possible that a well-maintained old installation may, in fact, be safer than a badly-maintained new installation. If the question of age is dealt with entirely on its own, I think that certain other aspects of the problem of the safety of electrical installations may be overlooked.

All these fires which have been reported have a known cause but there is a very large number of fires of which the cause is unknown. When the cause is known, it is a fairly reasonable assumption that the damage was such that traces of the cause were not destroyed. From this follows another possible assumption—that the installation was such that the spread of fire was in itself limited by the very nature of the installation. The location of cable runs and of equipment may play its part: in some cases it may have been responsible for a large fire, and in others for the fire being of negligible proportions. There has been little examination of the extent to which there has been a spread of fire. Undoubtedly there are many cases—they may have been included in this survey—where the fire was confined to the fuse-board.

Many consumers would resent having to install earth-leakage detectors, even if they could afford it. At the same time, I think that greater pressure should be brought to bear on the ordinary consumer to have his installation tested and checked thoroughly at frequent intervals, because this will reveal, not only earth leakage and insulation failure, but perhaps any unofficial and unauthorized connections and amateur wiring and other dangerous practices which could be discovered by the inspectors.

Mr. T. C. Gilbert: In Section 2 the author says that 'For obvious reasons the London area was excluded from the survey'. I cannot see the obvious in this case, and should like the author to explain this point.

In Section 8 he says that there is no single defect 'to which attack could be directed with the hope of an outstanding reduction in the number of fires'. I suggest that, on the contrary, Table 10 provides in a very significant way an indication of the direction to be pursued. It gives a sample of fires, and if we analyse the various systems which are listed there we find that metalclad wiring systems were responsible for nearly 80% of them—lead-covered cables for 25%, vulcanized rubber in conduit for 37%, and the remainder in mixed systems. It is reasonable

to assume that all the cases of contact with gas pipes were due to contact with these exposed earth-continuity conductors. Not a single group of the six escaped a fire with lead-covered cables, and only one with vulcanized rubber in conduit. I feel that this is an aspect of fire causation which the industry should take seriously to heart, even if it means rejecting some long-cherished ideas of what provides a good wiring system.

Allegations that electricity is a fire-raiser are, I think, unjustified; it is the installation which leads to the difficulties discussed in the paper. The paper confirms three ideas which I have held for many years. One is that an earth-continuity conductor should be treated as a conductor in its own right and not as a haphazard collection of iron, steel or lead. Furthermore, I think that an earth-continuity conductor should be regarded as a potentially live conductor, and therefore insulated against any extraneous contact. Thirdly, I think that we need to make a great deal more use of synthetic materials in cable insulation and sheathing. In this way we should escape the difficulty of the limited life of organic materials such as rubber, and probably prolong the life of our conductors very considerably. I feel that if these simple modifications could be brought into more common use, especially in the domestic-installation field, we should remove a great deal of the unjustified reproach which we now find levelled against electrical services.

Mr. J. I. Bernard: I should like to comment on the question of fires which are in some way associated with gas, and more particularly on the topical question of a new washing machine in which gas and electricity are associated in the same appliance. When the two services are brought together in this way, is it right to bond them together or to insulate the gas pipe from the electrical earth? The stock remedy for fixed installations is to bond gas pipes to conduits, in order to avoid fortuitous contact which might cause a spark and melting of a composition pipe. Many fires have been caused in this way. But for portable appliances there is another consideration which may weigh more against bonding. It is not brought out in the paper, and I should like the author to deal with it. In my experience the earth-continuity earth-loop resistance is lower through a gas pipe than through almost any electrical earth connection. Since current flowing through gas pipes is responsible for so many fires, it seems better to insulate the gas connection of a gas-heated electrically-driven washing machine. I should like the author's view.

Mr. G. E. B. Brunner: Does the author consider that, if a further survey were made on the basis of detailed technical information, it would be possible to draw more definite conclusions? If so, would it be feasible during a period of, say, one or two years for Area Board engineers to attend immediately at all premises involved in fires where Fire Service officers considered that the outbreaks were due to electrical causes, and for those Area Board engineers to make systematic checks in accordance with a predetermined plan and to complete standard questionaries?

Mr. G. E. D. Redman: I cannot understand why it is impossible to get 100 years' life from wiring by using mineral insulation, and am surprised that greater use is not made of mineral insulant instead of the organic material still employed to-day.

In the next 20 years there will be a great increase in the number of fires presumably due to the failures of cables. During the past 20 years many millions of yards of mineral-insulated cable has been used, and I feel sure that in the next 20 years those who use this material will play a great part in reducing the number of fires. This type of material, being inorganic, is more or less ageless; it is impervious to moisture when sealed, and because of its low-resistance copper sheath its earth continuity is beyond reproach.

I am worried by the fact that hundreds of thousands of houses are being bought to-day by young married couples with a mortgage spread over 20–25 years and wired with the cheapest material obtainable. By the time the owners have finished paying for the house they will have to pay for rewiring; and since neither screwed conduit nor mineral-insulated cable will have been used, this will necessitate a complete cable installation.

Mr. M. Beamont: In using conduits as earth-continuity conductors, we in many fault cases connect a potential to a widespread metal system; I have known many cases where the earth connection has broken and a fault has led to electric shocks being obtained over a wide area. The answer might be to use an earth-continuity conductor insulated throughout its entire run, together with conduit systems which are incombustible and non-conducting, so that if there is a breakdown through faulty cable insulation the fault is confined within the conduit, thus reducing risk of fire and shock.

Mr. C. J. Veness: I feel that if some of these fires were investigated, the blame could be attributed, not only to poor material, but also to very inferior workmanship.

The time is fast coming when we shall have to introduce compulsory regulations. The registration of operatives and contractors would go a long way towards solving the problem, and surely cannot be delayed much longer. Does the author believe that any of these fires can be attributed to defective workmanship?

I was interested to learn that many fires result from the service coming into the installation, the blame for which falls on the supply authority. In the new Regulations the question of the impedance of the supply authority's end of the earth loop has to be examined very carefully. The contractors and the Area Boards must get together and make sure that they comply with the relevant regulation in the 13th edition for limiting the impedance of the earth-loop circuit. In my view, the limitation of the earth-loop circuit impedance is very much in the hands of the Area Boards.

Mr. F. C. Walmsley: Indifferent workmanship is inexcusable, and one feels that the number of incidents due to faulty connections can be attributed to this cause. Nevertheless, it is general experience that fittings design is not conducive to ease of wiring, and the inaccessibility and smallness of terminations leave much to be desired. It is appreciated that fittings and accessory manufacturers endeavour to strive for compactness, but ease of connection should be kept in mind.

Mr. J. H. Mason (*communicated*): Some of the defects in service equipment may arise because these are often installed in consumers' kitchens, where the humidity is high and water and hydrocarbon vapours (grease) condense on leads and fittings. Rubber is attacked by many hydrocarbons, and I have seen v.r. insulated leads between the mains supply and the Board's meters and fuse-box which were covered in grease and completely perished. These leads had been installed for about 15 years. It may be inadvisable to install service equipment in kitchens or garages.

Mr. L. C. Roberts (*communicated*): It is common experience that the likelihood of breakdown and fire in an electrical installation grows as the age of the installation increases. The factors which influence the length of the safe life of an installation are many; some are inherent in the installation, such as the class of materials employed, the standard of workmanship and the fitness of the installation for the duties it has to perform. Other factors are the standard of maintenance (if any), conditions of operation, possible disturbances due to alterations or additions, and so on. All these variables are so important, and many so unpredictable, that any attempt to specify a figure for the safe life of a hypothetical average installation is a waste of time.

The one inherent factor which can be expected to bear a direct

relationship to the age of a given installation is the deterioration and eventual breakdown of insulation; and even this may be largely influenced by such external conditions as heat and moisture, or by the overloading of the conductors. The duration of the safe life of an installation is therefore impossible to forecast; it may remain safe for 50 years, or become dangerous at any time after its completion.

The further investigations envisaged by the author would presumably be directed at determining the safe life of specific types of installation; but the variables involved would be so numerous, and the research would necessarily extend over so long a period, that the results would probably be of little value on account of concurrent development of new materials and new techniques; in the meantime, a large proportion of the installations relevant to the investigations would in any case have become obsolescent.

Fires attributable to electrical causes will continue to occur so long as the cheap and nasty electrical contractor remains with us; so long as the way of the amateur handyman is made easy by the ready supply of wiring and accessories for his use—or misuse; until architects and others come to appreciate the functions of the consulting engineer; and until the general public realize that regular inspection and testing of an electrical installation, and proper maintenance, is a sound insurance.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. L. Gosland (*in reply*): It is first desirable to clear the questions of scope and interpretation raised by Mr. Hollingsworth, whose brief survey of cable types forms a valuable supplement to the paper. The data cover all fires reported to fire authorities, and thus include all classes of premises mentioned, although domestic were preponderant. Fires due to installations at more than 500 volts have been excluded. Table 2 correctly refers to 1 100 fires attributed to fixed wire and cable by the fire authorities, who had information on all fires: the 658 fires analysed in Table 4 were those on which Area Boards supplied information to the author. Of 537 cases in which judgment is possible, 210 were due to the wiring itself. The reason for the exclusion of London, questioned by Mr. Gilbert, was the impossibility of taking account of widespread bomb damage in assessing the population at risk.

The numerical data given in the discussion are of interest. Mr. Emerson suggests that, in his experience, the proportion of fires due to services is considerably lower than shown in the paper; but he records approximately 1 000 fires due to all electrical causes in ten post-war years, and thus, in 20 years, presumably less than 2 000, of which less than 100 were due to services. These figures cannot be said to differ significantly from those in the paper, namely 82 service fires in 1 100 due to fixed wire and cable, and thus probably in 2 500–3 000 due to all-electrical causes (Fig. A). Mr. Lawson's correlations are striking. It is agreed that few fires are due to overloading, but had his data shown wire and cable fires to increase with energy transmitted, I would have disputed the contrary conclusion. The flat characteristic shown appears to contradict the main conclusion of the paper; however, it is possible that the incidence of 1947–49 was seriously inflated by the early post-war experience, which is known to be abnormal.

It is true that, as Mr. Marryat indicates, the evidence in the paper suggests much more trouble from earth leakage than from leakage between conductors, but the evidence must be regarded as suspect because, in general, leakage to earth is much more readily diagnosed than the other. The widely held opinion of the value of earth-leakage protection is acknowledged, but the evidence in support provided by the paper is not of the strongest. Similarly, Mr. Gilbert, in advocating (like Mr. Beaumont) the elimination of metallic sheathing, can muster strong arguments, but, strictly, Table 10 of the paper does not provide him with evidence in support, unless he can make a satisfactory estimate of the proportions of the installations at risk which are respectively sheathed and unsheathed. I agree with Mr. Gilbert that the number of gas-pipe fires indicates a point to which attack could profitably be directed, but Mr. Redman would probably argue that the system he advocates also provides a remedy.

On the question of bonding or insulation of the exposed metalwork of gas and electric services, raised by Mr. Marryat and Mr. Bernard, a few fires have been caused by gas pipes melting away from any point of contact, and thus could have occurred with solid bonding; but the ascertained dangers of intermittent contact seem to justify serious study of all alternatives. As to portable appliances, the difficulty of maintaining earth continuity may well be as great with flexible gas pipes as with flexible electric supplies: thus it seems logical to isolate the flexible portions even if the fixed portions are bonded.

Mr. Swann's acceptance of the main conclusion of the paper is gratifying, but the evidence does not seem to disclose anything at which the electrical industry should be seriously embarrassed.

Mr. Strother Smith and Mr. Roberts draw attention to the factors other than age which may affect installations. The term 'ageing' is, of course, intended to cover not only chemical deterioration, but also any form of damage. The age parameter is capable of directing attention to a class of installation in which there is a high probability that in some way deterioration has occurred.

Mr. Mason and Mr. Walmsley make valuable points which might well be taken more strongly into account in standards and codes of practices. It seems possible that such factors as these are at least as common causes of fire as the simple bad workmanship to which Mr. Veness refers, but I have no satisfactory basis for an opinion on this point.

The survey described by the paper has been resumed, with an attempt to improve the liaison mentioned by Mr. Brunner. It is hoped that the results will be somewhat more conclusive than those of the present paper.

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Paper No. 1951 U
Dec. 1955

THE THEORY AND CHARACTERISTICS OF THE 3 : 1 POLE-CHANGING INDUCTION MOTOR

By T. H. BARTON, Ph.D., Associate Member, O. I. BUTLER, M.Sc., Member, and H. STERLING, Associate Member.

(*The paper was first received* 18*th July, and in revised form* 21*st September*, 1955. *It was published in December*, 1955, *and was read before the* UTILIZATION SECTION 16*th February*, 1956.)

SUMMARY

It is shown that the primary winding of a 3-phase induction motor, having p poles, say, may be reconnected to constitute a $3p$-pole winding of two or three symmetrical phase windings, the latter being little known and the former being a new type of pole-changing connection with considerable practical possibilities. Thus, a synchronous speed of one-third the normal value is obtained. It is noted that reconnection as an np-pole winding is possible, where n is any odd integer.

It is shown also that the performance characteristics of the motor for the $3p$-pole connection can be deduced satisfactorily from the design data of the machine, and that the single machine can be designed to provide characteristics which are comparable with those provided by two separate single-speed machines of standard design.

Also—for the first time so far as the authors are aware—an attempt is made to predict the performance of an induction motor from design data when the performance is appreciably affected by the presence of pronounced space harmonics of m.m.f. A satisfactory prediction is made possible only when the parameters include the "skew leakage reactance" component, which appears to have been ignored in the published work of this country. It is an important component of the unsaturated leakage reactance in the case of the harmonics of space m.m.f., and an important component also in the case of the fundamental space m.m.f. of a squirrel-cage induction motor having a full-pitch primary winding, and the customary degree of skew of the rotor bars.

LIST OF PRINCIPAL SYMBOLS

A_b = Cross-sectional area of rotor bars, in^2.
A_e = Cross-sectional area of end rings, in^2.
α = Angle of skew of rotor bars, electrical radians.
α_m = Angle of skew of rotor bars, mechanical radians.
B = Flux density, gauss.
B_m = Maximum flux density, gauss.
B_c = Maximum apparent flux density in core, kilogauss.
B_t = Maximum apparent flux density in teeth, kilogauss.
γ = Pitch of the stator coils, electrical radians.
β = Arc tan (sX_b/R_b).
d = Diameter of air-gap, in.
d_a = Diameter of rotor, cm.
d_1 = Mean diameter of stator end windings, in.
d_2 = Mean diameter of rotor end windings, in.
d_e = Mean diameter of end rings, in.
f = Supply frequency, c/s.
g_e = Effective air-gap length, in.
h_s = Depth of stator slot, in.
θ = Acute angle between a stator coil end and the core.
I_b = Current per rotor bar, amp.
K_d = Distribution factor of primary winding.
K_p = Pitch factor of primary winding.
K_s = Slot-leakage pitch factor.
K_{sk} = Skew factor of rotor bars, i.e. sin $\frac{1}{2}\alpha/\frac{1}{2}\alpha$.
k_t = Ratio of total magnetizing m.m.f. to that expended across the air-gap per pole.
l = Core length, in.
l_a = Length of rotor core, cm.
l_b = Length of rotor bars, in.
Λ_{s1} = Stator slot permeance, inch units.
Λ_{s2} = Rotor slot permeance, inch units.
m = Number of primary phases.
N = Number of primary conductors in series per phase.
N_b = Number of rotor bars.
N_1 = Number of stator slots.
P = Iron loss per primary phase, watts.
p = Number of poles of primary field.
q = Primary slots per pole per phase.
R_b = Effective resistance of rotor bar per centimetre length of core, ohms.
R_2 = Equivalent secondary resistance, in ohms, referred to primary, per phase.
R_m = Magnetizing resistance per primary phase, ohms.
r_1 = Ratio of stator effective tooth width to slot pitch.
r_2 = Ratio of rotor effective tooth width to slot pitch.
ρ_b = Resistivity of rotor bars, ohms/in/in^2.
ρ_e = Resistivity of end rings, ohms/in/in^2.
s = Fractional slip.
s_1 = Fractional slip referred to fundamental rotating field of normal connection.
s_5 = Fractional slip referred to 5th-harmonic rotating field of normal connection.
s_{t1} = Fractional slip referred to fundamental rotating field of triple-pole connection.
s_{t3} = Fractional slip referred to 3rd-harmonic rotating field of triple-pole connection.
T = Total torque on rotor, dyne-cm.
T_b = Torque per rotor bar, dyne-cm.
T_m = Maximum torque on rotor, dyne-cm.
t = Time, sec.
u = Linear velocity of flux wave relative to rotor, cm/sec.
V = E.M.F. per primary phase, volts, corresponding to B_c.
V_b = E.M.F. per rotor bar, volts.
v_c = Volume of actual iron of core, in^3.
v_t = Volume of actual iron of teeth, in^3.
ω_0 = $2\pi f$.
X_b = Effective reactance of rotor bar per centimetre length of core, ohms.
X_m = Magnetizing reactance per phase, ohms.
X_{o1} = Overhang-leakage reactance per primary phase, ohms.
X_{o2} = Equivalent secondary overhang-leakage reactance, ohms, referred to primary per phase.
X_{s1} = Primary slot-leakage reactance per phase, ohms.
X_{s2} = Equivalent rotor slot-leakage reactance, ohms, referred to primary per phase.
X_{sk2} = Equivalent rotor skew-leakage reactance, ohms, referred to primary per phase.

Dr. Barton and Mr. Butler are at the University of Sheffield.
Mr. Sterling is with Lancashire Dynamo and Crypto Ltd.

X_{z1} = Zig-zag leakage reactance per primary phase, ohms.
X_{z2} = Equivalent zig-zag leakage reactance of rotor, ohms, referred to primary per phase.
y = Displacement from zero position of flux wave at time zero, cm.
Y_2 = Axial distance from rotor core to centre of end-ring, in.
Z_b = Effective impedance of rotor bar per centimetre length of core, ohms.

(1) INTRODUCTION

The speed control of induction motors has received a great deal of attention, and various well-known methods have been evolved from time to time, all of which detract from the inherent simplicity of the motor to varying extents. The most recent is that of Williams and Laithwaite,[1] utilizing a new principle which may be of practical value in obtaining continuous speed control, above the normal speed, for a motor of very special construction.

The present paper is concerned with a pole-changing method using a single winding to obtain two values of pole-number in the ratio of 3 : 1, although the method may be extended to obtain any pole-number ratio of n : 1, where n is odd. Creedy[2] has shown that various pole-number ratios can be obtained from a single winding by reconnecting it for various numbers of phases, the supply to which is obtained from a phase transformer. Single windings can also be designed so that by reconnection it is possible to obtain pole number ratios of 2 : 1, 3 : 2, 4 : 3, 5 : 4, etc., when excited by a 3-phase supply at both speeds. However, up to the present, the pole-number ratio for a single winding has been restricted to 2 : 1 in practice,[3] since the use of a special transformer can be avoided in this case and the number of motor connections can be kept within reasonable limits. Barton and Doxey[4] have shown that the application of the Görges phenomena affords an alternative method of obtaining a synchronous-speed ratio of 2 : 1 in slip-ring induction motors. In general, with all such methods, the arrangement conforming with accepted winding practice is the one which provides the higher speed, and thus the methods provide reduction, rather than increase, in the normal speed of the motor.

Applications exist where a synchronous-speed ratio greater than 2 : 1 is desired, e.g. certain machine-tool drives and hoists and lifts, and the usual procedure has been to fit two separate windings of different pole-numbers. This scheme has the advantages of flexibility in the choice of speeds and a small number of motor terminals, but since two separate stator windings are required, the labour costs are high and the motor must be derated considerably to provide the additional winding space as well as the compromise magnetic circuit of a two-speed machine. In place of dual-wound motors, two separate single-speed motors mounted in tandem are sometimes used, especially where the ratio of speeds is large and slip-ring control is required on one speed. Both schemes are therefore relatively expensive and result in a large moment of inertia—which on some drives may be a disadvantage. Brown and Butler[5] have shown that it is possible to obtain a synchronous-speed ratio of 3 : 1, using the simple zero-sequence connection. However, it is effectively a single-phase connection and therefore can provide neither a starting torque nor the normal full-load motoring torque without an increase in the size of the motor.

The method of the present paper discusses a little-used principle,[6] namely balanced operation of the motor on a harmonic field produced by the interconnection of parts of each normal phase winding. Important practical applications of the principle exist and are discussed in a paper being prepared by the authors. The purpose of the present paper is to demonstate that a 3 : 1 pole-changing motor can be designed to provide a satisfactory overall performance, and to show that such a motor need not necessarily be larger or more expensive than a single-speed motor for either speed.

(2) SUB-PHASE PRINCIPLES

It will be shown that each phase of a 3-phase winding comprises two or more "sub-phases."

(2.1) Phase Winding as Multiple Sub-Phase Windings

In general, each phase winding of a 3-phase motor occupies either one-third or two-thirds of each pole-pitch; i.e. each phase winding has a spread of either 60° or 120°. Evidently, when the winding has an integral number of slots per pole per phase of q, say, each phase spread can be subdivided into q equal "sub-phase" spreads of either $60°/q$ or $120°/q$, respectively. Thus, each phase winding of 60° or 120° spread can be subdivided into q sub-phase windings, successively displaced by $60°/q$ or $120°/q$, respectively, and having a spread of $60°/q$ or $120°/q$, respectively.

In particular, if q is a multiple of 2, each phase winding can be subdivided into two sub-phase windings displaced by 30° or 60°, respectively, and having a spread of 30° or 60°, respectively. Similarly, if q is a multiple of 3, each phase winding can be subdivided into three sub-phase windings displaced by 20° or 40°, respectively, and having a spread of 20° or 40°, respectively.

(2.2) Symmetrical Sub-Phase Systems

Let A, B and C in Fig. 1 represent the phase windings per double-pole pitch of a 3-phase motor for which the number of



Fig. 1.—Division of normal into triple-pole winding phase spread.

slots per pole per phase, q, is a multiple of 3 and the phase spread is 60°. Also, let the three sub-phase windings of any one phase winding be represented by the addition of the numerals 1, 2 and 3 to the letter representing the phase winding. Thus, for example, the phase winding A comprises the sub-phase windings A1, A2 and A3 which are located in space by the electrical angular positions of 0°, 20° and 40°. Similarly, the sub-phase windings B1, B2 and B3 are located in space by the electrical angular positions of 120°, 140° and 160°, whilst the sub-phase windings C1, C2 and C3 are located at 240°, 260° and 280°.

Obviously, the sub-phase windings A1, B1 and C1 comprise a symmetrical 3-phase winding which, when connected for zero-sequence excitation, provides a 3rd-harmonic magnetic field at the air-gap of the motor.[5] Similar third-harmonic fields are provided by the zero-sequence excitation of either of the symmetrical 3-phase windings comprising the sub-phase windings A2, B2, C2, and A3, B3, C3, respectively. For convenience, let the separate zero-sequence connected 3-phase windings of A1, B1, C1 and A2, B2, C2 and A3, B3, C3 be referred to as the "3rd-harmonic windings," and let them be represented more succinctly by ABC1, ABC2 and ABC3, respectively.

It will be seen that the 3rd-harmonic windings ABC1, ABC2,

and ABC3 are *successively* displaced electrically in space by 60° on the basis of one cycle of the 3rd-harmonic field occupying 360° electrically in space, and have a phase spread of 60°. Further, if the 3rd-harmonic winding ABC2 is regarded as having its "start" and "finish" interchanged, the three windings are *mutually* displaced electrically in space by 120°. Thus, the windings may be excited by a balanced 3-phase supply to provide a 3-phase 3rd-harmonic field which has a resultant m.m.f. having a constant peak magnitude equal to 1·5 times that of each winding and which rotates in space at a synchronous speed of one-third the normal synchronous speed of the motor.

It may be noted that when the normal phase spread is 120°, instead of the 60° assumed above, the 3rd-harmonic windings have a phase spread of 120° on the basis of the 3rd-harmonic field, and they are then mutually displaced by 120° without interchange of the "start" and "finish" of one of the 3rd-harmonic windings.

Further, when the normal number of slots per pole per phase, q, is a multiple of 2, and the normal phase spread is 60°, a pair of 3rd-harmonic windings ABC1 and ABC2 can be derived, each with a spread of 90° on the basis of the 3rd-harmonic field, and displaced from each other by 90° in space. Thus, the pair of 3rd-harmonic windings may be excited by a balanced 2-phase supply to provide a 2-phase 3rd-harmonic field which has a resultant m.m.f. having a constant peak magnitude equal to that of each 3rd-harmonic winding, and which rotates in space at a synchronous speed of one-third the normal synchronous speed of the motor.

Also, when the normal number of slots per pole per phase is neither 2 nor 3, nor a multiple of these, it is still possible to obtain two or three sub-phases provided that the number of slots per pole per phase of the 3rd-harmonic or "triple-pole" connection, r, is a figure for which a balanced winding can be produced, as discussed in Section 11.1.

In general, it may be noted that if each normal pole-pitch (Fig. 1) of a p-pole winding contains $3nr$ slots, where n is any odd number and r is any number, the coils may be connected such that a 3-phase, np-pole winding having r slots per pole per phase is obtained. Alternatively, if each normal pole-pitch contains $2nr$ slots, a 2-phase np-pole winding having r slots per pole per phase is obtained.

(2.3) Practical Examples

In order to demonstrate more clearly the principle of reconnecting for triple-pole operation, two examples are described. The first, illustrated in Fig. 2, shows a connection for 3-phase

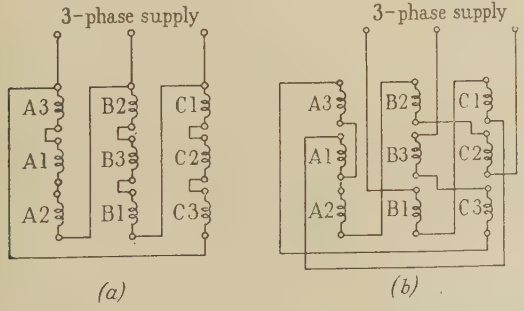


Fig. 2.—Example of 3-phase p-pole to 3-phase $3p$-pole connection.
(a) 3-phase, p-poles.
(b) 3-phase, $3p$-poles.

triple-pole operation. The winding is normally a delta-connected fully-pitched 3-phase winding with a 60° phase spread, and its phases are split into three sub-phases. For operation at one-third speed the sub-phases are connected in series for zero sequence as outlined above, and the triple-pole phases thus obtained are connected in star. A total of 14 terminals are required, and the mean flux density in the gap and teeth during triple-pole operation is approximately 170% of the flux density during normal operation. While this relationship appears to indicate an excessive variation in densities, it is shown in Section 11.2 that this ratio will give approximately equal peak torques for both speeds and does not necessarily require an increase in frame size beyond that required for a single-speed motor. It should be noted that the flux density in the stator and rotor cores during triple-pole operation is only about 56% of the normal core flux density.

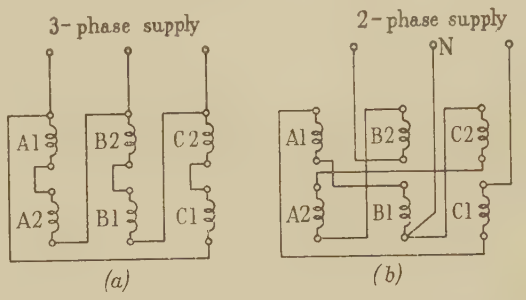


Fig. 3.—Example of 3-phase p-pole to 2-phase $3p$-pole connection.
(a) 3-phase, p-poles.
(b) 2-phase, $3p$-poles.

The second example, illustrated in Fig. 3, shows a connection for 2-phase triple-pole operation, where the 2-phase supply is obtained from a Scott-connected transformer. The winding is fully-pitched and delta-connected, and has a phase spread of 60°. It is split into two sub-phases per phase. For triple-pole operation, each of the two phases consists of three sub-phases connected in series. The Scott-connected transformer can, of course, be wound for any voltage but, in practice, the output voltage will be such as to give a triple-pole gap flux-density of 150–170% of the full-speed gap flux-density. For this scheme only nine motor terminals are required.

It should be noted here that a short-chording with respect to the fundamental pole pitch of $y°$ will result in a corresponding short-chording of $3y°$ for the triple-pole connection; i.e. a short-chording of 20°, resulting in a normal chording factor of 0·985, will correspond to a triple-pole chording of 60° and a chording factor of 0·866.

Before proceeding with a more detailed theoretical discussion of the parameters involved in an analysis of the performance of the motor when connected for balanced triple-pole operation, it will be helpful to study actual test results of its performance.

(3) NORMAL AND TRIPLE-POLE TEST RESULTS

Two machines were tested, each being single-cage motors with the primary windings having a phase spread of 60°. The first machine had been designed for normal operation, without any attention to its performance as a triple-pole motor, and was representative of the class having more or less equal equivalent secondary and primary resistances per phase when referred to, say, the primary circuit. The second machine was also one of standard design, except that a 4-pole winding was fitted to a standard 8-pole core having a larger stator bore and a greater number of stator and rotor slots than a standard 4-pole core, in order that a compromise magnetic loading could be obtained for normal and triple-pole operation. It was representative of the "high resistance rotor" class of machine.

Machine No. 1 was the 3-phase 4-pole 50 c/s 7·5 h.p. 400-volt squirrel-cage induction motor used by Brown and Butler.[5] The stator winding coils were full-pitch with a phase spread of 60° and fitted in a total of 36 slots, i.e. three slots per pole per phase.

Machine No. 2 was a 3-phase 50 c/s 400-volt squirrel-cage induction motor. The nominal continuous rating of the frame size, when fitted with a low-resistance rotor as an 8-pole machine, was 7·5 h.p. The stator winding coils were full-pitch with a phase-spread of 60° and were fitted in a total of 48 slots, i.e. four slots per pole per phase.

An induction regulator was used to provide a constant-voltage supply at 50 c/s for the induction motor, which was direct-coupled to a separately-excited, d.c. machine. The latter provided a simple means of torque measurement, by the measurement of its armature current for a fixed field current, which is more convenient than, and as accurate as, the use of a dynamometer machine.

A Ward Leonard set was utilized to give precise speed control of the d.c. machine and direct-coupled induction motor under test. A Scott-connected transformer was used to obtain a balanced 2-phase supply for triple-pole operation of machine No. 2.

The current, power and torque were measured over the speed range 2 000 r.p.m. forwards to 2 000 r.p.m. backwards. The tests were performed at reduced voltage and current so that temperature changes of the winding during a test could be neglected. It has been confirmed that results so obtained may be extrapolated to normal voltages with reasonable accuracy, provided that magnetic saturation is allowed for by the use of open-circuit and short-circuit characteristics, and bearing in mind that the effect of the harmonics may become less pronounced.

The measured torque, power and current to speed characteristics of machine No. 1, when operated on its normal connection at 187 volts per phase and when operated on the triple-pole connection at 87 volts per phase, are shown in Fig. 4. The voltages are such that the air-gap flux density for the triple-pole connection is about 34% higher than that for the normal connection; an increase that has been deduced experimentally to be about the maximum which can be used with this machine if undue saturation is to be avoided on the triple-pole connection when the voltages are extrapolated to the corresponding values of 400 and 187 volts per phase. It therefore follows that a step-down transformer would be required for the triple-pole connection of this particular machine to the supply lines.

Similar characteristics for machine No. 2 at 90 and 75 volts per phase, respectively, are shown in Fig. 5, the air-gap flux density for the triple-pole connection being then about 70% greater than that for the normal connection. Such a relative increase is possible since, in avoiding undue saturation of the stator core for the normal connection at full voltage, the air-gap flux density is somewhat lower than the customary value (see Section 11.2).

Thus the characteristics provide a fair comparison of the performance of the two machines, although measured at reduced voltages, since they represent the relationship between normal performance and the best triple-pole performance that can be obtained in practice from each machine.

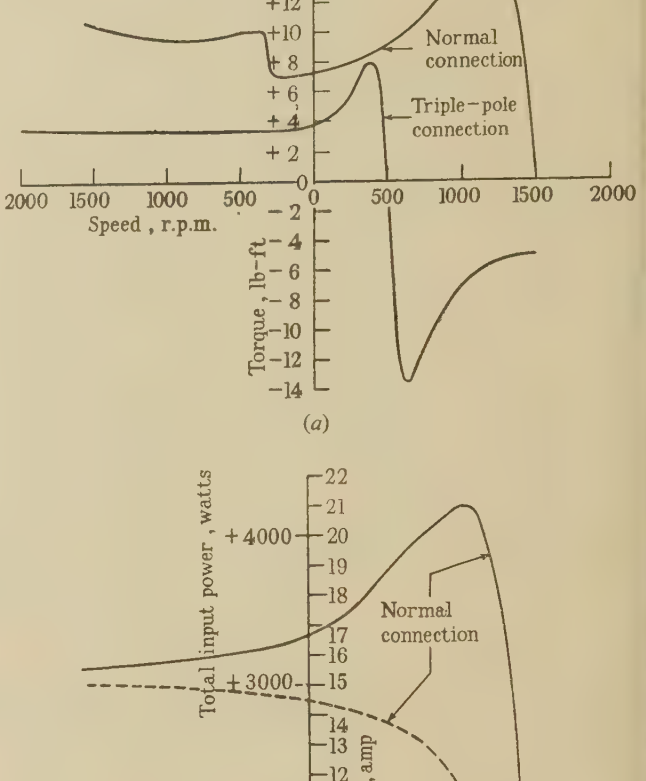


Fig. 4.—Normal and triple-pole characteristics of machine No. 1.

Normal characteristics at 187 volts/phase; triple-pole characteristics at 86·6 volts/phase.
(*a*) Torque/speed curves.
(*b*) Input-power/speed curves ————. Phase-current/speed curves — — — —.

(4) DISCUSSION OF RESULTS

Fig. 4 shows that the peak torque of machine No. 1 for triple-pole operation is approximately 50% of that for normal operation. This is appreciably better than the theoretical figure of 33·3% (as discussed in Section 11.2), owing to the increased magnetic loading for triple-pole operation.

However, it should be pointed out that, by suitable design, it is possible to obtain a compromise magnetic circuit between the ideals for a p- and a $3p$-pole motor. This involves the use of a larger stator bore and a larger number of stator and rotor slots than the standard for a p-pole motor, resulting in a smaller stator core depth than is usual in a p-pole motor. The stator-core flux density therefore becomes the limiting factor during full-speed operation. As a result of this, the air-gap and teeth flux density during full-speed operation will be less than usual. The peak torque will, however, not necessarily be smaller than usual because of the larger diameter and the reduced leakage reactance

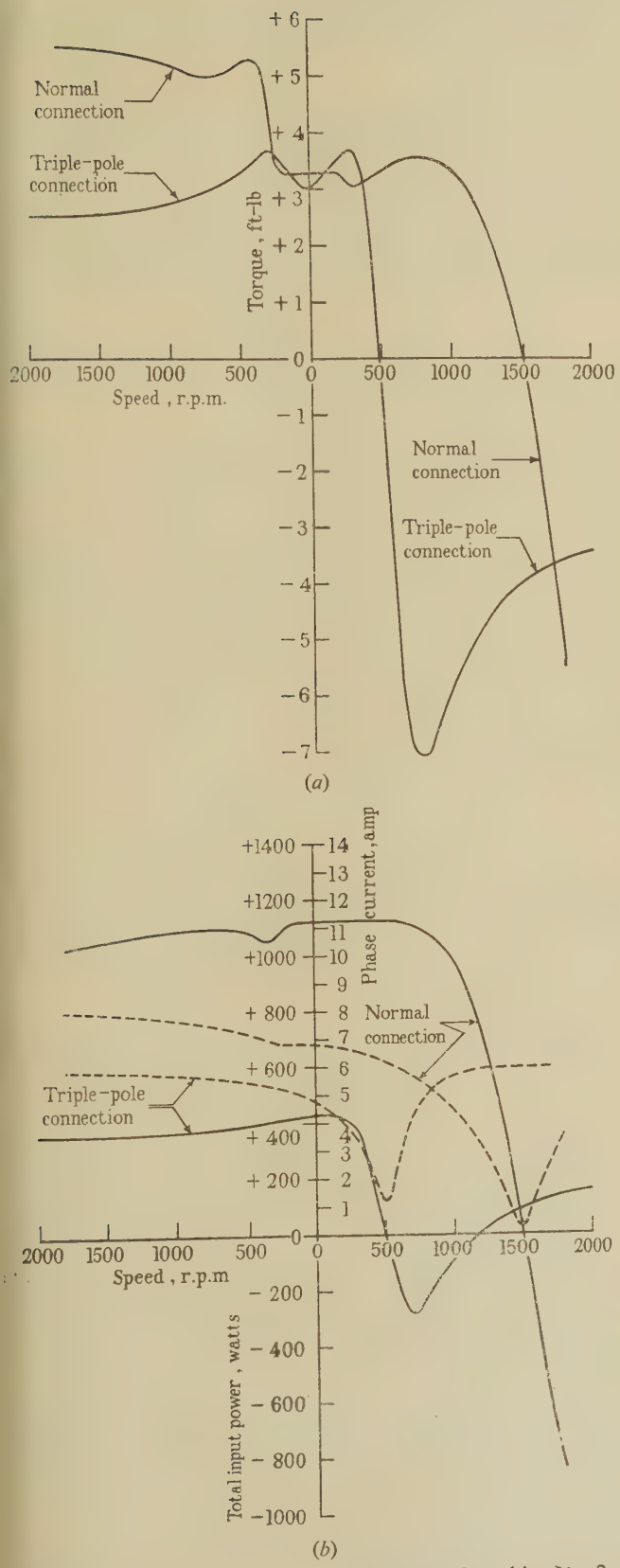


Fig. 5.—Normal and triple-pole characteristics of machine No. 2.
Normal characteristics at 90 volts/phase; triple-pole characteristics at 75 volts/phase.
(*a*) Torque/speed curves.
(*b*) Input-power/speed curves ————.
Phase-current/speed curves — — — —

due to the larger number of slots. During triple-pole operation, the limiting factor is the flux density in the air-gap and the stator and rotor teeth, while the flux density in the cores is relatively low and unimportant. As has been pointed out above, the full-speed air-gap flux density with a compromise design will be less than the permissible maximum value and it is therefore possible to increase the air-gap flux density during triple-pole operation. Section 11.2 shows that the peak torque, for a given lamination, varies approximately as the square of the air-gap flux density and inversely as the number of poles. If it is possible to increase the triple-pole air-gap flux density to about 1·7 times the full-speed air-gap flux density, the same peak torque should be obtained at either pole-number.

Fig. 5 shows that the use of a compromise design, i.e. a standard $2p$-pole core-plate coupled with the required variation of air-gap flux densities, can result in a $3p : p$ pole-changing motor providing the same peak torque at either pole-number. This is a most encouraging result, particularly since the full-speed peak torque is not much less than it would be on a standard p-pole design with normal air-gap densities, owing to the larger stator bore and the increased number of rotor and stator slots. Typical values of the ratio of outside core-diameter to stator bore are given by Kuhlman[7] and can be used as a guide to help in choosing a suitable stator bore for a compromise design.

It will be seen that the torque/speed curves in Figs. 4 and 5 do not take the usual theoretical form. However, they are not unusual in practice for squirrel-cage induction motors, except for the somewhat large harmonic effects resulting from the use of full-pitch windings. They are in close agreement with the theoretical deduction of Section 11.2, that the separate triple-pole and normal curves are of the same form, except for different effects of higher harmonics in each case due to the difference in winding factor for the stator and skew factor for the rotor.

With regard to starting torques and currents, and making allowance for the step-down transformer of machine No. 1, the triple-pole starting torque and line current are about 50% and 30% respectively, of those for the normal connection. In the case of machine No. 2, and making allowance for the Scott-connected transformer, the triple-pole starting torque and line currents are about 100% and 40%, respectively, of those for the normal connection. It follows that the starting conditions may be improved by direct-on-line starting with the triple-pole, rather than the normal, winding connection.

It follows that the compromise design, using a $2p$-pole core plate for the $3p : p$ pole-changing motor results in an overall performance which is comparable with the performance of two separate single-speed designs for $3p$- and p-poles. However, for constant-torque drives, the need for providing a compromise magnetic circuit may necessitate a slight increase in frame size beyond that of either of the two equivalent standard single-speed motors.

(5) PREDICTION AND COMPARISON OF NORMAL AND TRIPLE-POLE PARAMETERS

The results obtained with machine No. 2 demonstrate the advantages obtained by the use of a design which is a compromise between the high- and low-speed requirements. Further assistance in obtaining the best compromise is afforded by the availability of expressions for both the normal and triple-pole parameters, since the effect of detailed changes in design on the overall performance of both connections can then be more readily assessed.

It is therefore proposed to set down in turn known or deduced expressions for determining the parameters from the design data, and to comment briefly upon the relative values of the normal and triple-pole parameters.

The expressions for leakage reactance were taken from a readily available source[8] and rearranged so as to show most clearly the influence of various factors on the motor performance at either pole-number. No attempt has been made to correct for saturation of the leakage paths, which materially reduces the zig-zag, slot-tip and skew leakage reactances during high current loadings. Since all tests were taken at low voltages, where the saturation effect is negligible, this aspect of induction-motor performance should cause no discrepancies between calculated and tested results.

(5.1) Secondary Impedance referred to the Primary

Consideration will be restricted to the case of a squirrel-cage machine in expressing the secondary values as equivalent primary values per phase.

(5.1.1) Equivalent Secondary Resistance.

The best expression for the equivalent secondary resistance,[9] in ohms, is

$$R_2 = \frac{m}{10^6}\left(\frac{NK_pK_d}{K_{sk}}\right)^2\left[\frac{\rho_b l_b}{N_b A_b} + \frac{\rho_e \pi d_e}{N_b^2 A_e}\frac{1}{2\sin^2(\pi p/2N_b)}\right] \quad . \quad (1)$$

It should be noted that a simpler and more widely used expression exists,[10] which replaces the trigonometrical term by $0{\cdot}64 d_e\rho_e/p^2A_e$. This expression assumes a large number of slots per pole, and may therefore result in error when calculating triple-pole performance or the effect of harmonics. Since the error is confined to the term relating to the equivalent end-ring resistance, and since this varies approximately inversely as the square of the number of poles, the total error introduced by using the simplified equation is not very great unless the end-ring component of the effective resistance per bar is relatively large.

Thus, R_2 will differ for triple-pole and normal operation due to the differences in K_p, K_d, K_{sk}, p and possibly m and N.

(5.1.2) Equivalent Slot-Leakage Reactance.

The equivalent slot-leakage reactance, in ohms, is

$$X_{s2} = \frac{2fm\Lambda_{s2}}{10^7 \times N_b}\left(\frac{NK_pK_d}{K_{sk}}\right)^2 \quad . \quad . \quad . \quad . \quad (2)$$

Thus, X_{s2} will differ for triple-pole and normal operation owing to the differences in K_p, K_d, K_{sk} and possibly m and N.

(5.1.3) Equivalent Overhang-Leakage Reactance.

Numerous formulae, more or less empirical, have been proposed for the calculation of overhang-leakage reactance. The following expression, based upon a detailed mathematical analysis, and therefore of most general application, has recently been derived by Alger[11] for the total overhang-leakage reactance, referred to the primary winding, per phase.

$$X_0 = \frac{4{\cdot}6\, fmd_1N^2}{10^8p^2}(ab + 0{\cdot}93cK_p^2) \quad . \quad . \quad . \quad (3)$$

where

$$a = (\gamma - \sin\gamma)(\tan\theta)/\pi$$

$$b = 1 - (0{\cdot}8d_2/d_1)^{p/2}$$

$$c = \log\frac{1{\cdot}4d_1}{h_s} - \frac{d}{d_1} \times \log\left(\frac{0{\cdot}54d}{R}\right)$$

$$R = [(\tfrac{1}{2}d_1 - \tfrac{1}{2}d_2)^2 + (Y_1 - Y_2)^2]^{1/2}$$

$$Y_1 = \frac{d_1}{p}\tan\theta\tan\left(\frac{\gamma}{4}\right)$$

the logarithms being to the base 10. As recommended by Alger,[11] the equivalent overhang-leakage reactance of the secondary winding will be taken as

$$X_{o2} = \tfrac{1}{2}X_o \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3c$$

Thus X_{o2} will differ for triple-pole and normal operation due to the differences in p, K_p, γ, and possibly m and N.

(5.1.4) Equivalent Zig-Zag Leakage Reactance.

One of the equations given by Alger[12] for the equivalent zig-zag leakage reactance, in ohms, may be rewritten as

$$X_{z2} = \frac{5{\cdot}25fmdl}{10^8 g_e}\left(\frac{Nr_2}{N_b}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (4$$

Thus, X_{z2} may differ for triple-pole and normal operation due to the possible differences in m and N.

(5.1.5) Equivalent Skew-Leakage Reactance.

The equivalent skew-leakage reactance, in ohms, is given by Alger,[13] and may be rewritten as

$$X_{sk2} = \frac{0{\cdot}133fmdl}{10^8 \times k_i g_e}(\alpha_m NK_pK_d)^2 \quad . \quad . \quad . \quad . \quad (5$$

Thus, X_{sk2} will differ for triple-pole and normal operation owing to the differences in K_p, K_d and possibly m and N.

(5.2) The Magnetizing Impedance

(5.2.1) The Magnetizing Reactance.

The magnetizing reactance, in ohms, is given by Alger[14] as

$$X_m = \frac{6{\cdot}4\, fmdl}{10^8 \times k_i g_e}\left(\frac{NK_pK_d}{p}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (6$$

Thus, the triple-pole reactance is approximately one-ninth the normal reactance, depending upon the appropriate values of K_p and K_d for the case of constant m and N.

It should be noted that even with very low flux densities, the factor k_i is appreciably greater than unity for machines having a small air-gap length.

(5.2.2) The Magnetizing Resistance.

The iron loss, in watts per phase, at 50 c/s is given by Carr[14]

$$P = (0{\cdot}059B_c^2v_c + 0{\cdot}082B_t^2v_t)/m \quad . \quad . \quad . \quad . \quad (7$$

Since the frequency of the magnetizing current is 50 c/s for both the normal and triple-pole connection, the same dynamic hysteresis loop is applicable in each case for the same maximum flux density. Thus, the effective angle of lag of the flux density behind the magnetizing force is the same in each case; i.e. the ratio of the magnetizing resistance to the magnetizing reactance is the same for both normal and triple-pole operation, for the same maximum flux density. Further, it may be deduced from the work of Butler and Mang[16] that the maximum flux density may vary appreciably with little change in the effective angle of lag.

Hence, for an e.m.f. per phase of V volts corresponding to the maximum flux density of B_c, the magnetizing resistance in series with the magnetizing reactance per phase may be taken, in ohms, as

$$R_m = \left(\frac{X_m}{V}\right)^2 P \quad . \quad . \quad . \quad . \quad . \quad . \quad .$$

since, in general, $X_m \gg R_m$.

It will therefore be seen that both the triple-pole resistance and reactance, and consequently the impedance, are appro

nately 1/9 times the values for normal operation, depending upon the appropriate values of K_p and K_d, for the case of onstant m.

(5.3) Primary Impedance per Phase

5.3.1) Primary Resistance.

The primary resistance per phase is readily obtained and will liffer for normal and triple-pole operation only if there is a lifference in the number of conductors in series per phase arising rom a difference in the number of phases or the use of different umbers of parallel circuits per phase.

5.3.2) Slot-Leakage Reactance.

The slot-leakage reactance per phase, in ohms, is

$$X_{s1} = \frac{2fmN^2}{10^7 N_1} K_s \Lambda_{s1} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where K_s is the slot-leakage pitch factor as evaluated by Alger.[17] Thus, X_{s1} will differ for normal and triple-pole operation if he number of phases differ for the two cases. It should be urther noted that, unless the coils are fully-pitched, the value of K_s is different for the normal and triple-pole connections. When ull-pitch coils are used, K_s is unity in both cases.

(5.3.3) Overhang-Leakage Reactance.

As recommended by Alger,[11] the overhang-leakage reactance, in ohms per phase, may be taken as

$$X_{o1} = X_{o2} = \tfrac{1}{2} X_o \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where X_o is given by eqn. (3).

Thus, X_{o1} will differ for triple-pole and normal operation in he same way as X_{o2}, as discussed in Section 5.1.3.

(5.3.4) Zig-Zag Leakage Reactance.

One of the equations given by Alger[12] for the zig-zag leakage reactance per phase, in ohms, may be rewritten as

$$X_{z1} = 5 \cdot 25 fmdlK_s (Nr_1/N_1)^2 / 10^8 g_e \quad . \quad . \quad . \quad (11)$$

Thus, X_{z1} may differ for triple-pole and normal operation owing to the possible changes in m and N. Again it should be noted that, when the coils are not full-pitch, the effective values of X_{z1} will be somewhat different for normal and triple-pole connection, owing to a difference in the value of K_s.

(6) PREDICTION OF PERFORMANCE CHARACTERISTICS

The above expressions for the triple-pole and normal parameters have been used to predict the performance of machine No. 2. Account was taken of the pronounced fifth space-harmonic of air-gap m.m.f. present on normal operation, by including its equivalent circuit in series with that of the fundamental space harmonic,[18] and similarly for the third space-harmonic on 2-phase triple-pole operation (see Fig. 7). The expressions in Section 5 refer to the parameters of the fundamental circuits for triple-pole and normal operation. The expressions applicable to the magnetizing and secondary circuits may also be utilized to calculate the parameters of a harmonic circuit by using the appropriate value of pole-number and quantities dependent upon the pole-number. It should be noted that the harmonic overhang-leakage reactance of the secondary winding may be evaluated from the fundamental value, in the case of a squirrel-cage motor, by considering that it varies inversely as the square of the order of the harmonic.

The relevant design details of machine No. 2 are given in Table 1 and Fig. 6, and Table 2 gives the values of the normal

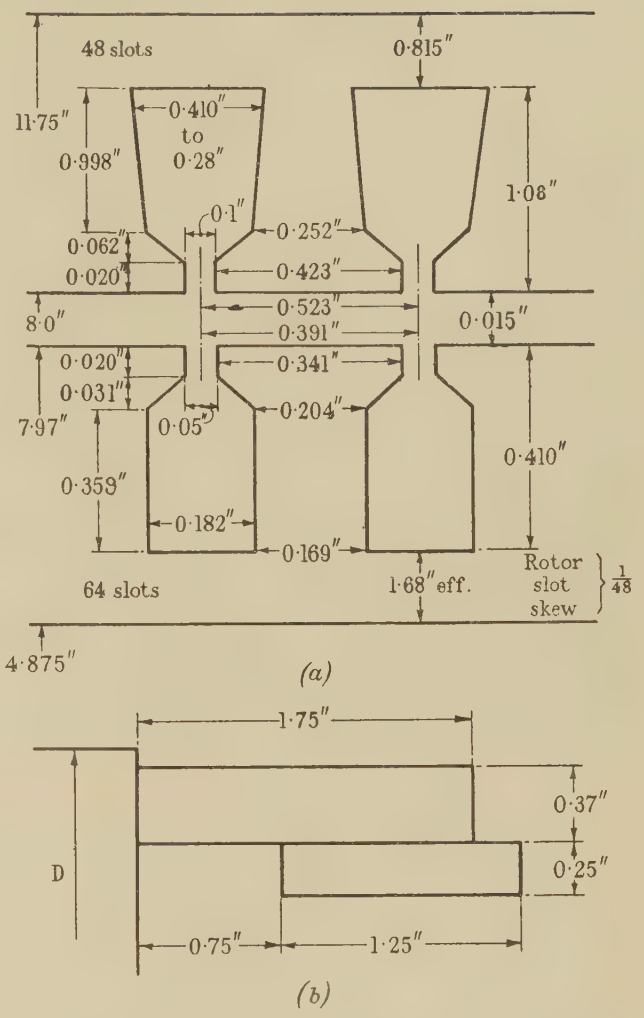


Fig. 6.—Details of stator and rotor slots, and rotor end-winding.
(*a*) Stator and rotor slots.
(*b*) Rotor bar and end-ring.

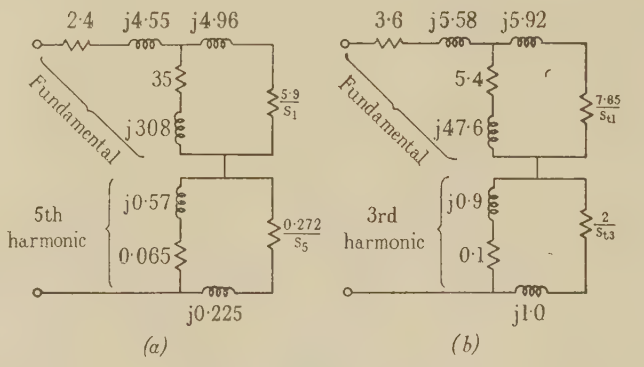


Fig. 7.—Equivalent circuits.
(*a*) Normal connection.
(*b*) Triple-pole connection.

and its 5th harmonic, as well as the triple-pole and its 3rd-harmonic components of the parameters. Thus, the equivalent circuits for normal and triple-pole operation, respectively, with the predicted values of the parameters, may be shown as in Figs. 7(*a*) and 7(*b*) in which the fractional slips s_1, s_5, s_{t1}, s_{t3} are

Table 1

DESIGN DETAILS OF MACHINE NO. 2

	Stator	Rotor
Type of winding	Lattice	Squirrel cage
Number of slots	48	64
Pitch of coil	Full	
Slot skew	None	1 stator slot
Conductors in series per phase	640	1
Conductor size	0·064 in	0·37 in × 0·17 in
Conductor section	0·003 22 in²	0·061 in²
Length of M.H.T.	15·5 in	
Bar effective length		6·24 in
Resistivity at 75° C	0·825 microhms/in/in²	3 microhms/in/in²
End-ring size		1·25 × 0·25
End-ring resistivity at 20° C		0·68 microhms/in/in²
End-ring mean diameter ..		6·9 in
Gross core length	4 in	4 in
Net core length	4 in	4 in
Net iron length	3·6 in	3·6 in

Table 2

ESTIMATED VALUES OF VARIOUS COMPONENTS OF FUNDAMENTAL AND HARMONIC PARAMETERS, IN OHMS, FOR NORMAL AND TRIPLE-POLE CONNECTIONS OF MACHINE NO. 2

	Normal		Triple-pole	
	Fundamental	5th harmonic	Fundamental	3rd harmonic
R_2	5·9	0·272	7·65	2·0
X_{s2}	0·94	0·051	1·44	0·38
X_{o2}	1·23	0·049	0·64	0·07
X_{z2}	1·04	0·044	1·37	0·17
X_{sk2}	1·75	0·081	2·47	0·41
X_m	308	0·57	47·6	0·90
R_m	35	0·065	5·4	0·1
R_1	2·40	—	3·59	—
X_{s1}	1·69	—	2·52	—
X_{o1}	1·23	—	0·64	—
X_{z1}	1·63	—	2·42	—

referred to the normal, 5th-harmonic, triple-pole and triple-pole 3rd-harmonic synchronous speeds, respectively. The winding resistances are based upon a temperature of 50° C.

The performance characteristics calculated from Fig. 7(*a*) for a supply voltage of 90 volts are shown as continuous curves in Fig. 8. Also those calculated from Fig. 7(*b*) for a supply voltage of 75 volts are shown as continuous curves in Fig. It will be seen that reasonable agreement is obtained between t predicted and test results of current and input power for bo the normal and triple-pole connections of the motor, but t predicted and test results of the torque/speed characteristics a not in such close agreement. The predicted results will be so what in error because the 7th and other harmonics and t variation of rotor resistance and leakage reactance with f

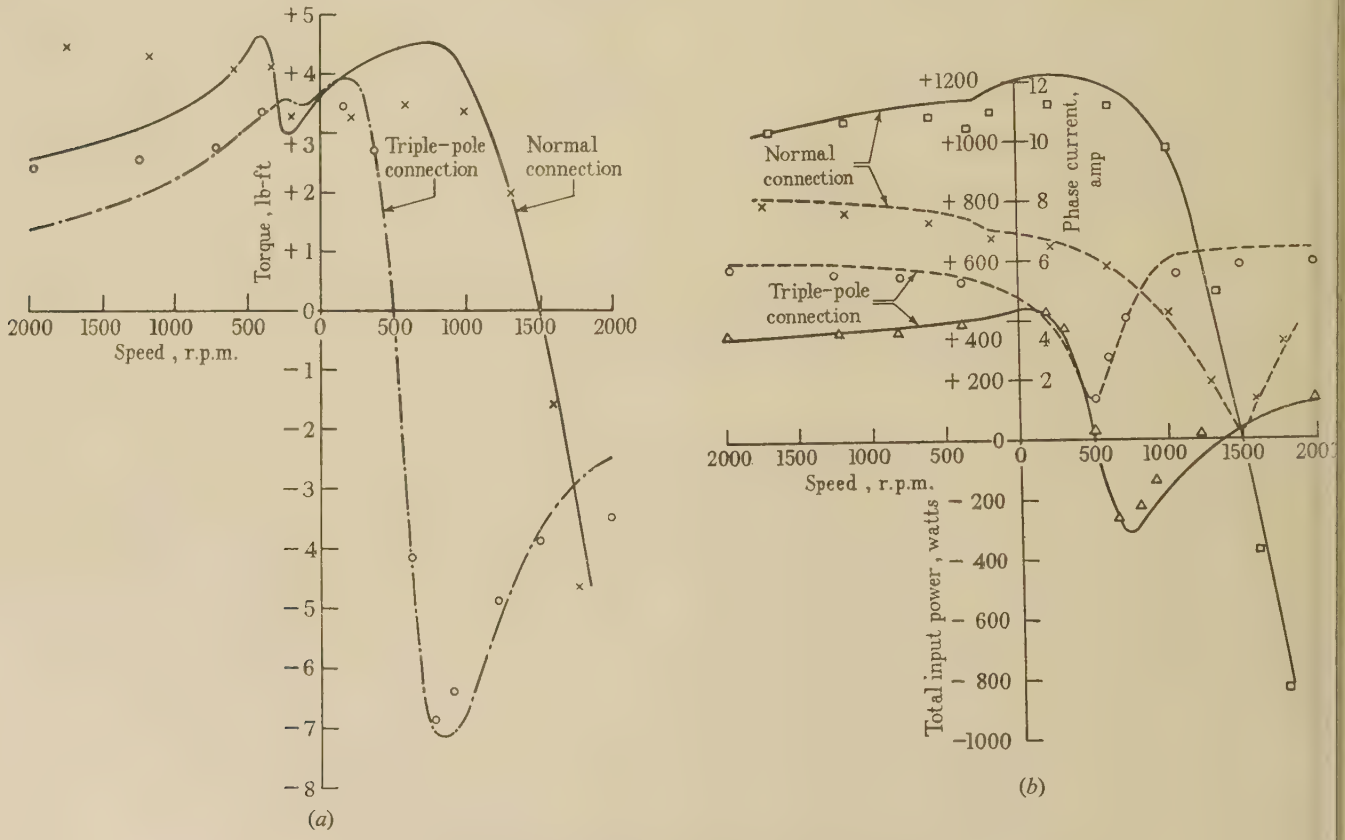


Fig. 8.—Predicted and measured characteristics of machine No. 2.

Normal characteristics at 90 volts/phase. Triple-pole characteristics at 75 volts/phase.

(*a*) *Torque/speed characteristics.*

Normal: calculated ——
Normal: experimental ×
Triple-pole: calculated —·—·—
Triple-pole: experimental ○

(*b*) *Predicted total input power* ——
Predicted phase currents — — —
Normal measured current ×
Triple-pole measured current ⊙
Normal measured power ⊡
Triple-pole measured power △

quency are ignored. The measured torque curve indicates that the effect of the neglected harmonics is small. Also, calculations show that the effect of variation of rotor frequency is small, owing to the use of shallow bars of high resistivity.

The difference between the measured and predicted torque/speed curves suggests that it arises mainly from ignoring the "stray loss" torque. The latter is of the order of magnitude to be expected in a squirrel-cage machine, and obeys approximately the empirical rule given by Morgan, Brown and Schumer,[19] i.e. that the stray-loss power is proportional to the square of the product of the motor speed and current.

(7) COMPARISON OF RATINGS OF SINGLE-SPEED AND SINGLE-WINDING DUAL-SPEED MOTORS

A general-purpose motor of the same frame size as the experimental machine No. 2 has a continuous rating of 3 and 15 h.p. for operation as a 12- and 4-pole motor, respectively. As a single-winding 3 : 1 pole-changing motor, the air-gap flux density can be so arranged that, with the same frame size as previously, the continuous ratings are, respectively, 3 and 12 h.p. Alternatively, for a constant-torque drive the continuous ratings would be 3 and 9 h.p. respectively. In both cases the temperature rise would not exceed that permitted by the relevant British Standard.

It should be borne in mind that the range of pole-numbers for the more economical designs of single-speed motor is somewhat limited, and the lower and upper limits of the range tend to increase with the frame size. Thus, when two single-speed motors are required to provide the same torque at speeds in the ratio of 3 : 1, the frame size of one motor may need to be considerably larger than that of the other. In this case, the larger frame size will usually be sufficient for the dual-speed machine to provide the same alternative outputs as those provided by the two separate single-speed motors.

It will be appreciated that a dual-speed machine utilizing a compromise magnetic circuit cannot provide performance characteristics which are identical with those of the corresponding two single-speed motors. In particular, at the higher speed of the pole-changing machine the power factor is greater than that of the corresponding single-speed motor, owing to the use of a flux density in the air-gap which is lower than normal. However, at the lower speed the reverse is the case, since the air-gap is longer than normal to permit satisfactory operation of the pole-changing machine at the higher speed.

It is of interest to note that, in discussing the 3 : 1, 3-phase-to-3-phase single-winding pole-changing motor, Sequenz[6] considers that it is essential to maintain the same value of air-gap flux density at the alternative speeds, and suggests the use of short- or long-chorded coils to achieve this result. Evidently this procedure reduces materially the output available from a given frame size. An alternative winding arrangement is considered, which increases the winding factors to 0·985 and 0·866 for the lower and higher pole-numbers, respectively. However, it is concluded that the arrangement is of little practical value, since it requires a total of 36 terminals on the motor. The present paper shows that a full utilization of the single winding can be made at both speeds, without the need for an excessive number of terminals.

(8) CONCLUSIONS

It is shown that a pole-changing induction motor with a speed ratio of 3 : 1 is capable of providing an overall performance comparable with the performance of two separate and standard motors, having corresponding pole numbers, when the pole-changing motor uses the same frame size as the single-speed motors.

The circuit parameters of the pole-changing motor can be determined with reasonable accuracy for both of the alternative connections to enable a satisfactory prediction of the corresponding performance characteristics, particularly when due regard is paid to stray-loss effects.

It is demonstrated—for the first time, so far as the authors are aware—that in predicting the performance characteristics of an induction motor from design data, the appreciable effect of pronounced space harmonics of m.m.f. may be taken into account with reasonable accuracy. This is possible only when the leakage reactance of the secondary circuit includes the skew-reactance component—a component which appears to have been completely ignored in the published works of this country.

The results obtained indicate that the skew-reactance is an important component of the unsaturated secondary leakage reactance in the consideration of the effect of the harmonics of space m.m.f. of a squirrel-cage motor having a full-pitch primary winding and the customary degree of skew of the rotor bars. It is also an important component in the consideration of the effect of the fundamental space m.m.f. of a pole-changing motor operating at either speed. It should be pointed out, however, that the skew leakage reactance is appreciably affected by saturation of the leakage-flux paths, and is therefore less important when the current loading is large, i.e. during starting at full voltage.

(9) ACKNOWLEDGMENTS

The facilities provided by the University of Sheffield, and the concurrence of Lancashire Dynamo and Crypto Ltd., in the publication of the paper, are gladly acknowledged.

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(11) APPENDICES

(11.1) Case of Non-Integral Number of Slots per Pole per Sub-Phase

When the number of slots per pole per phase, q, for normal operation is such that it is impossible to obtain an integral number of slots per pole per sub-phase, it is still possible to obtain a balanced 3- or 2-phase triple-pole winding if a double-layer winding is used and the well-known conditions for a winding of $3p$-poles are satisfied. It will be appreciated that such conditions can, in general, be satisfied more readily in practice for a 2-phase than for a 3-phase triple-pole winding.

In general, the number of slots will be such as to permit a standard and balanced winding for both the normal and triple-pole connection. Nevertheless, even when the number of slots does not conform with the accepted rules for a balanced triple-pole winding, it should be noted that, by a careful allocation of unequally distributed winding turns over the phase spread, it may still be possible for the triple-pole winding to be made very nearly, if not exactly, symmetrical electrically so as to constitute an acceptable winding arrangement.

(11.2) The Effect of Pole Number on Peak Torque of a Squirrel-Cage Motor with Fixed Frame Size

The flux density, B gauss, at any instant of time, t seconds, and at any point displaced y cm from the zero position of the flux wave at $t = 0$, is

$$B = B_m \sin (py/d_a - s\omega_0 t)$$

where $s\omega_0$ is the electrical angular velocity of the flux wave relative to the rotor.

The e.m.f. (in volts) induced in a rotor bar at the displacement y is

$$V_b = ul_a B \times 10^{-8}$$

where

$$u = s\omega_0 d_a/p$$

Thus

$$V_b = \frac{s\omega_0 l_a d_a B_m}{p \times 10^8} \sin (py/d_a - s\omega_0 t)$$

and the current, in amperes, produced in the bar is

$$I_b = \frac{s\omega_0 d_a B_m}{pZ_b \times 10^8} \sin (py/d_a - s\omega_0 t - \beta) \quad . \quad . \quad (12)$$

where $Z_b = R_b + jsX_b$, $\tan \beta = sX_b/R_b$, and R_b and X_b represent, respectively, the effective resistance and reactance of the rotor circuit per bar in ohms per unit length of bar at the supply frequency of $f_0 = \omega_0/2\pi$, such that R_b and X_b include the end-ring effect.

The torque on the bar, in dyne-cm, produced by the interaction of I_b and B, is

$$T_b = Bl_a d_a I_b/20$$

$$= \frac{s\omega_0 l_a d_a^2 B_m^2}{2pZ_b \times 10^9} \sin (py/d_a - s\omega_0 t) \times \sin (py/d_a - s\omega_0 t - \beta)$$

That is,

$$T_b = \frac{s\omega_0 l_a d_a^2 B_m^2}{4pZ_b \times 10^9} [\cos \beta - \cos (2py/d_a - 2s\omega_0 t - \beta)]$$

consists of a constant component and a component varying at a frequency of $2sf_o$. Since the latter component varies in phase from bar to bar, its resultant value for all bars is zero, and the total torque on the rotor is

$$T = \frac{s\omega_0 l_a d_a^2 N_b B_m^2}{4pZ_b \times 10^9} \cos \beta.$$

That is,

$$T = \frac{\omega_0 d_a^2 l_a N_b B_m^2}{4p \times 10^9} \frac{R_b/s}{(R_b/s)^2 + X_b^2} \quad . \quad . \quad . \quad (13$$

It can be shown that for constant B_m, T attains its peak value o

$$T_m = \omega_0 d_a^2 l_a N_b B_m^2 / 8pX_b \times 10^9 \quad . \quad . \quad . \quad (14$$

when

$$s = R_b/X_b \quad . \quad . \quad . \quad . \quad . \quad . \quad (15$$

Hence, with reference to eqn. (14), the peak torque of a given squirrel-cage rotor, for a given air-gap flux density, is inversely proportional to the number of stator poles. In particular, the peak torque with $3p$-poles is 33·3% of that with p-poles. However, eqn. (12) shows that the reduction is due to the current per bar being reduced to 33·3%, and the peak torque with $3p$-poles may therefore be improved by increasing B_m to the limit of the permissible temperature rise of the motor.

It is of interest to note from eqn. (13) that the shape of the torque/speed characteristic is sensibly unaffected by the number of poles, for a given rotor and air-gap flux density, since R_b and X_b remain sensibly constant. Evidently, for the practical case of constant supply voltage, the air-gap flux density tends to fall as the slip increases, mainly owing to the presence of the primary leakage reactance. Hence, in practice, the magnitude and shape of the torque/speed characteristic is influenced by the total, rather than the secondary, leakage reactance. However, since this effect is common to operation with any number of poles, the shape of the torque/speed characteristic remains sensibly unaffected by the number of poles. It will be appreciated from the equations in Section 5 that, when the resistance and leakage reactance of the end-windings are abnormally large, a change in the number of poles will cause the values of the equivalent secondary resistance and total leakage reactance to change considerably, and consequently the magnitude and shape of the torque/speed characteristic will be affected by the number of poles.

Further, eqn. (14) shows that, in the 3 : 1 pole-changing motor, the air-gap flux density must be increased $\sqrt{3}$ times at the lower speed to provide the same peak torque at both speeds. Such an increase can be obtained (*a*) by reducing B_m at the higher speed to less than the customary value while increasing d_a and N_b to maintain more or less the same peak torque, and (*b*) by increasing B_m at the lower speed to greater than the customary value since the electric loading of the machine is much reduced [see eqn. (12)]. Evidently, reducing B_m at the higher speed to less than the customary value provides the additional advantage that undue saturation of the stator core at full voltage is avoided, particularly since the number of stator slots may also be increased with d_a.

[The discussion on the above paper will be found on page 316.]

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Feb. 1956

APPLICATIONS OF THE 3:1 POLE-CHANGING MOTOR

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SUMMARY

Besides the obvious application of providing two separate and economical running speeds, the application of the 3 : 1 pole-changing motor to obtain controlled starting, stopping and reversing of industrial drives is considered in some detail. For the latter types of drive, an investigation is made of the energy loss involved, and a comparison with other methods of control is made.

It is shown that various asymmetrical connections of the primary winding for the larger pole-number can provide useful characteristics, for both squirrel-cage and slip-ring machines, and, in general, a 2-phase connection of the primary winding for the larger pole-number is likely to be more satisfactory than a 3-phase connection.

LIST OF PRINCIPAL SYMBOLS

I = Moment of inertia, lb-ft^2.
N = Speed, r.p.m.
N_s = Synchronous speed, r.p.m.
P = Power loss, watts.
R_1 = Primary circuit resistance, ohms.
R_2 = Equivalent secondary circuit resistance, ohms.
s = Fractional slip.
T = Torque, lb-ft.
W = Energy loss, joules.
W_0 = Ideal energy loss in secondary circuit, joules.

(1) INTRODUCTION

It has been shown by the authors[1] that a single-winding $3p : p$ pole-changing induction motor can be designed to provide characteristics which are comparable with those provided by two separate, single-speed machines of standard design, where p represents the number of poles for which the machine is wound as a 3-phase motor. The same peak torque can be provided at both speeds, and the winding may be reconnected as a $3p$-pole machine having either two or three phases.

The availability of the lower synchronous speed is a particular advantage for drives which are continuously, or frequently, starting, stopping and/or reversing. Starting can be effected with high torque, low currents and reduced energy loss, whilst regenerative braking can be used from full to one-third speed to give a minimum of heating of the motor during stopping, with symmetrical connections of the windings in each case.

Alternatively, one of the many possible asymmetrical connections[2] of the lower-speed winding arrangements may be used to provide a comparatively simple method of braking from full speed, with low energy loss. Noodleman[3] has discussed such an arrangement, in the case of squirrel-cage motors, which is being usefully applied to machine-tool and other drives, despite the fact that the motor carries a separate winding for the lower pole number. Obviously, a great deal is gained by using a single winding for both pole numbers, as in the present 3 : 1 pole-changing motor of more or less standard design.

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Various symmetrical connections of the primary windings will first be dealt with, and this will be followed by a discussion of various symmetrical connections of the secondary circuit, and the application of both symmetrical and asymmetrical primary-winding connections with alternative forms of secondary circuit.

(2) SYMMETRICAL PRIMARY CONNECTIONS

The symmetrical connections may conveniently be divided into those providing 3-phase and those providing 2-phase windings for the lower speed or triple-pole operation, and each may be subdivided into arrangements requiring different numbers of motor terminals. For the purpose of the present paper, discussion is limited to the case where the mean flux density in the air-gap during triple-pole operation is arranged to be about 170% of that for full-speed or normal operation, to provide approximately equal peak torques for both speeds. It has been shown previously[1] that this can readily be attained with standard core-plates.

In practice, a somewhat lower ratio of air-gap flux densities of 150%, say, may result in improved overall performance on constant-torque drives, whilst for variable-torque drives other ratios of the air-gap flux densities may be desirable. It may be noted, also, that even when a transformer is required for triple-pole operation, to obtain the desired air-gap flux density and number of phases, its apparent-power rating is comparatively low.

(2.1) 3-Phase/3-Phase Connections

The two main arrangements differ owing to the need for, or for the avoidance of, a transformer for low-speed operation at a phase voltage approximately 58% of that for high-speed operation, when the number of parallel paths per phase is the same in each case.

(2.1.1) Connection without a Transformer.

Referring to Fig. 1, it will be seen that each of the normal phases A, B, C is divided into three sub-phases, as previously defined by the authors.[1] The winding is delta-connected for the smaller and star-connected for the larger number of poles, to give the desired air-gap flux density in the latter case without the use of a transformer. The phase-spread is 60° in each case, and it will be seen that a total of 14 terminals is required, which necessitates somewhat elaborate control equipment. However, in the case of large motors operating for long periods at each alternative speed, this may not be a serious disadvantage.

(2.1.2) Connection with a Transformer.

With reference to Fig. 2, the winding is delta-connected for both the smaller and larger number of poles, with three parallel paths per phase in the latter case and with a phase-spread of 120° in each case.[4] It will be seen that the number of terminals has been reduced to nine, and the complication of the necessary control equipment is therefore considerably reduced.

Alternatively, with reference to Fig. 3, the winding may be

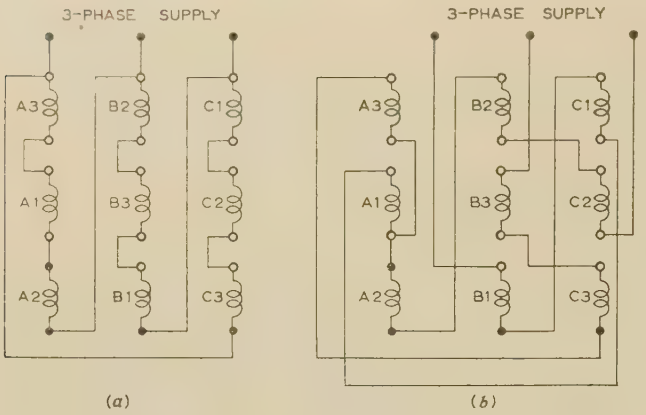


Fig. 1.—Example of 3-phase p-pole to 3-phase $3p$-pole connection.
(a) 3-phase p-pole.
(b) 3-phase $3p$-pole.
o Terminals.

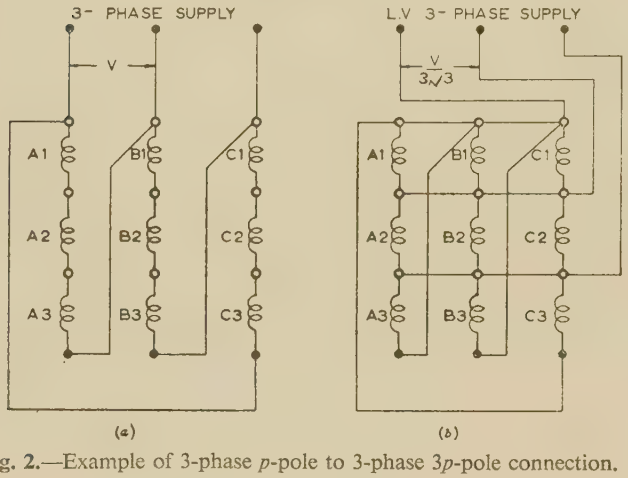


Fig. 2.—Example of 3-phase p-pole to 3-phase $3p$-pole connection.
(a) 3-phase p-pole.
(b) 3-phase $3p$-pole.
o Terminals.

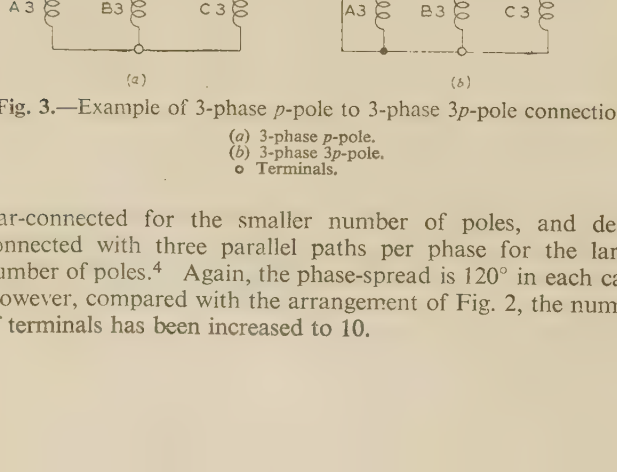


Fig. 3.—Example of 3-phase p-pole to 3-phase $3p$-pole connection.
(a) 3-phase p-pole.
(b) 3-phase $3p$-pole.
o Terminals.

star-connected for the smaller number of poles, and delta-connected with three parallel paths per phase for the larger number of poles.[4] Again, the phase-spread is 120° in each case. However, compared with the arrangement of Fig. 2, the number of terminals has been increased to 10.

(2.2) 3-Phase/2-Phase Connections

It may be shown that in this case approximately equal pea torques are obtained at both speeds when, with the same numbe of parallel paths per phase for both speeds, the phase voltage a the lower speed is 87% of that at the higher speed of operation

It is essential that the 2-phase supply shall be correctly balance when it is required to operate the motor at the lower speed fo prolonged periods. Fig. 4 shows that this can readily be achieve

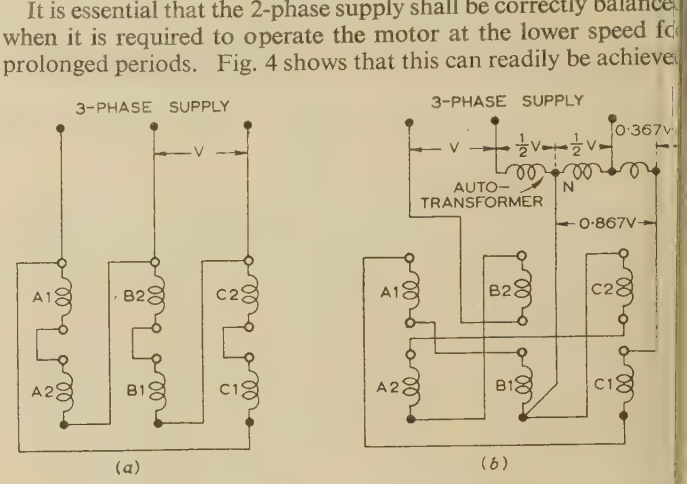


Fig. 4.—Example of 3-phase p-pole to 2-phase $3p$-pole connection.
(a) 3-phase p-poles.
(b) 2-phase $3p$-poles.
o Terminals.

by means of a single auto-transformer, to provide the desire relationship between the phase voltages at the higher and lowe speeds of operation.[5]

It will be seen that the motor winding is delta-connected fo high-speed operation and requires a total of nine terminal The transformer apparent-power rating is only 33% of that o the motor for low-speed operation, and, allowing for the increase magnetizing current of the motor at the lower speed, it is approx mately one-sixth of the apparent-power rating of the motor a the higher speed. The 3-phase line currents are balanced, an equal in magnitude to the 2-phase currents.

Alternatively, the motor winding may be star-connected fo high-speed operation, as shown in Fig. 5, utilizing a Scot

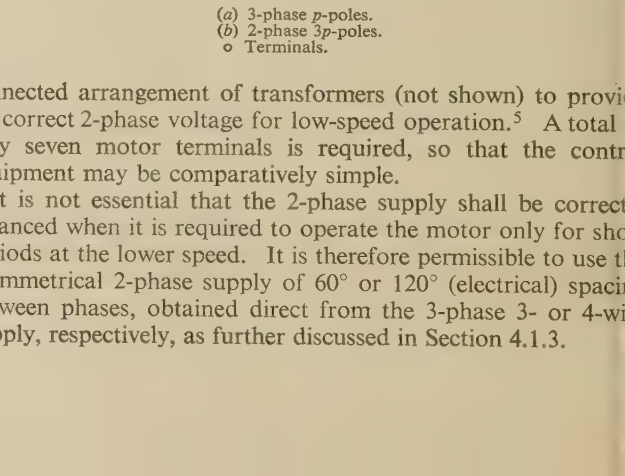


Fig. 5.—Example of 3-phase p-pole to 2-phase $3p$-pole connection.
(a) 3-phase p-poles.
(b) 2-phase $3p$-poles.
o Terminals.

connected arrangement of transformers (not shown) to provid the correct 2-phase voltage for low-speed operation.[5] A total o only seven motor terminals is required, so that the contro equipment may be comparatively simple.

It is not essential that the 2-phase supply shall be correct balanced when it is required to operate the motor only for sho periods at the lower speed. It is therefore permissible to use th asymmetrical 2-phase supply of 60° or 120° (electrical) spacin between phases, obtained direct from the 3-phase 3- or 4-wi supply, respectively, as further discussed in Section 4.1.3.

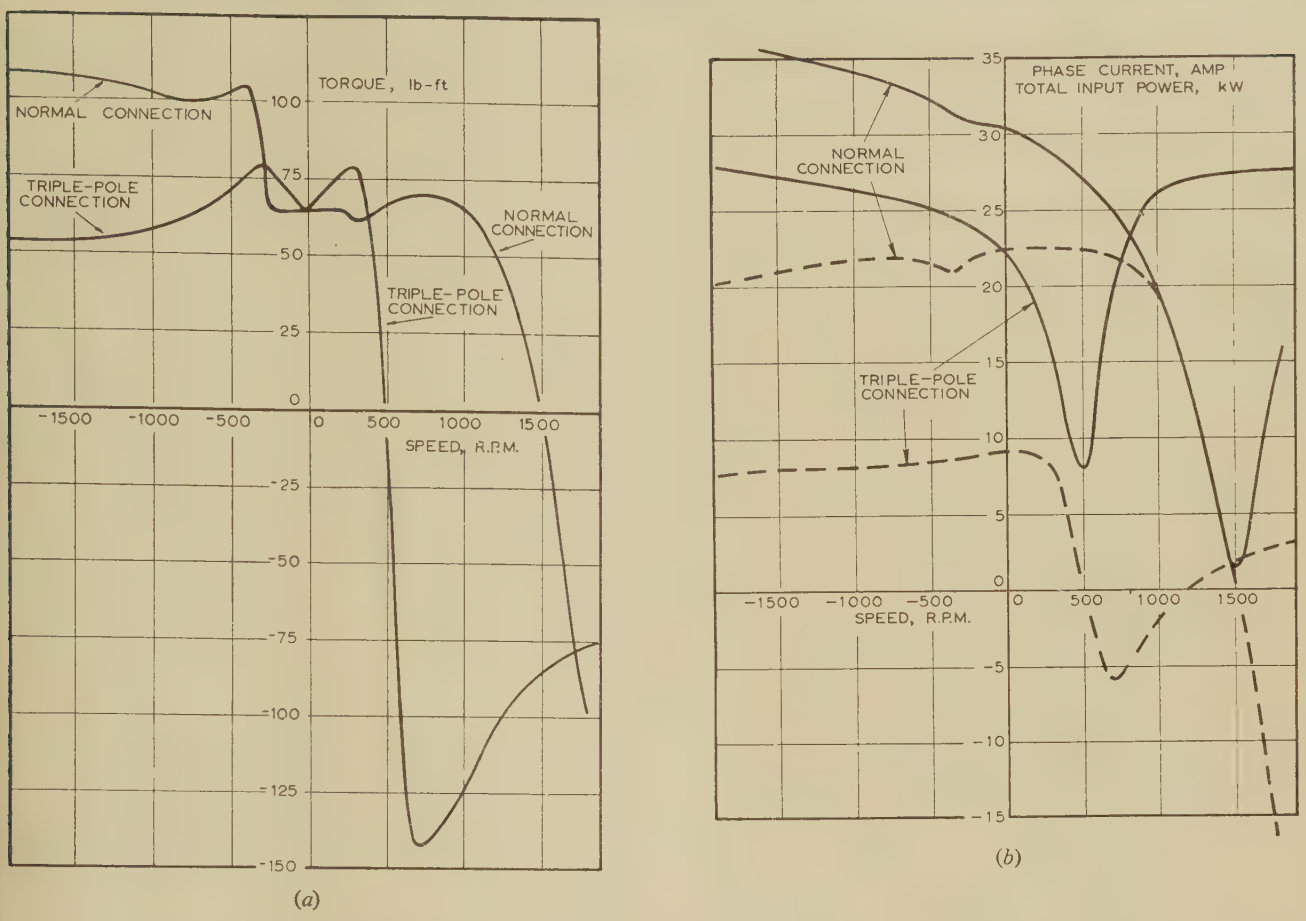


Fig. 6.—Normal and triple-pole characteristics of the experimental machine.

(*a*) Torque/speed characteristics. (*b*) Phase-current/speed and total-input-power/speed characteristics.

———— Phase current.
— — — — Total input power.

(2.3) Performance Characteristics

The performance characteristics at both speeds of an experimental squirrel-cage induction motor, representative of the "high-resistance rotor" class of machine, are given in Fig. 6, the motor being connected in accordance with Section 2.2. It may be noted that the experimental motor is that cited as machine No. 2 by Barton, Butler and Sterling.[1] The nominal continuous rating of the machine frame size at 750 r.p.m., when fitted with a conventional "low resistance" rotor, is 7·5 h.p. with a 3-phase 50 c/s supply. The stator coils are full-pitched with a phase-spread of 60°, and are fitted in a total of 48 slots.

It will be seen that in consequence of the use of full-pitch coils, a pronounced 5th-harmonic effect exists in the torque/speed curve for the normal connection, and a pronounced 3rd-harmonic effect exists in the torque/speed curve for the triple-pole connection. Otherwise, although the torque/speed curves do not take the usual theoretical form, they are not unusual in practice for squirrel-cage motors.[6]

Further, it will be seen that both the power consumption and current from standstill to the lower synchronous speed of 500 r.p.m. are considerably less with the triple-pole than with the normal connection. It should also be noted that Fig. 6 has been deduced from low-voltage tests of the motor by linear extrapolation. This is not strictly correct, owing to saturation of the leakage-flux paths at high currents, and in practice the torques, currents and powers will be somewhat greater[7] than as shown in Fig. 6.

(3) SYMMETRICAL SECONDARY CIRCUITS

Obviously, a single- or multiple-cage secondary circuit should be utilized whenever possible with pole-changing motors. Alternatively, when widely different secondary resistance values are required at the lower and higher speeds (e.g. to obtain a high starting torque) an unconventional brushless machine may be used which is effectively a double-cage machine at the higher speed and a single-cage machine at the lower speed, as discussed below.

However, when a wound secondary circuit with slip-rings is required to obtain speed control at the higher and lower speeds, one of several forms of single secondary winding may be used.

(3.1) Unconventional Brushless Rotor

Advantage may be taken of the fact that a single- or multi-turn coil short-chorded by one-third of the normal pole pitch has zero effective mutual inductance with the primary winding when the latter is connected for triple-pole operation. Thus, a secondary winding consisting of such coils, which may be short-circuited by a common end-ring at one side of the rotor, responds to the normal connection of primary winding only. If the rotor is fitted also with a conventional cage winding, the performance characteristics for operation on the normal and triple-pole connections may be made to differ widely to suit special applications, as further discussed in Section 4. Again, a somewhat smaller degree of short-chording may be used to obtain other and still different performance characteristics for low- and high-

speed operation. Alternatively, the short-chorded and short-circuited coils may be replaced by a conventional fully-pitched star-connected secondary winding, with the three phase-ends permanently connected to each other, since a star-connected secondary winding has zero effective mutual inductance with the primary winding when the latter is connected for triple-pole operation.

(3.2) Single-Winding Rotor Circuits

Figs. 7 to 9 show three of the several possible forms of single-winding rotor circuit. Each phase-winding of Figs. 7 and 8 is

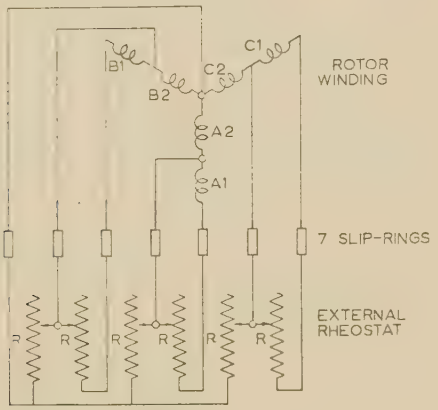


Fig. 7.—Single-winding rotor circuit.

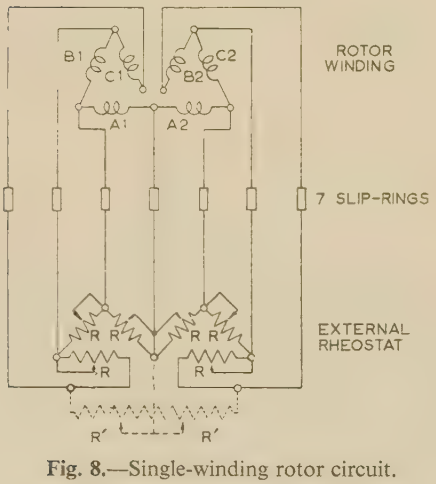


Fig. 8.—Single-winding rotor circuit.

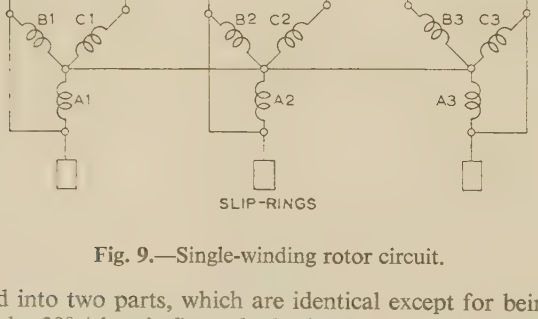


Fig. 9.—Single-winding rotor circuit.

divided into two parts, which are identical except for being displaced by 30° (electrical) on the basis of the lower pole-number. It will be seen, therefore, that the parts A1, B1, C1 and A2, B2, C2 form the phases of a balanced 2-phase triple-pole winding. Evidently, the resistors R permit speed control on both the triple-pole and normal connections of the windings.

In addition, in the case of Fig. 8, only two extra resistors, R′, are required to allow independent setting of the necessary circuit resistance for triple-pole and normal operation, in conjunction with appropriate contactors, which is advantageous in those applications where the resistance is required to be changed rapidly when the pole-number is changed. Seven slip-rings are required for each of the windings of Figs. 7 and 8. A further alternative is a 5-phase 36°-spread p-pole winding having only five slip rings and external resistors, which again provides resistance control at both speeds.

Fig. 9 illustrates a single-winding rotor circuit requiring only three slip-rings. The p-pole arrangement comprises three separate star-connected windings, each of which is permanently short-circuited. The $3p$-pole arrangement comprises a star-connected winding, each phase having three parallel paths, connected to external resistance via the slip-rings. Thus, this form of rotor circuit may be used to control the starting and braking torques, as well as the speed, from near standstill to one-third speed; it is further discussed in Section 4. It should be noted that when the phase-spread is 60°, the winding A2, B2, C2 of Fig. 9 is reverse-connected, compared with the remaining windings, in order to obtain a balanced 3-phase winding during triple-pole operation. Obviously, such a balanced winding may be delta-connected on $3p$ poles rather than star-connected, if so desired.

(4) APPLICATIONS

The applications of the 3 : 1 pole-changing motor may conveniently be divided into those utilizing either symmetrical or asymmetrical connections of the primary windings.

For frequent start-stop and reversing drives, various symmetrical and asymmetrical connections of the primary windings may be utilized. Such alternative arrangements may be compared on the basis of the energy dissipation in the motor circuit per duty cycle.

Theoretical expressions for the energy dissipation have been developed, using certain simplifying assumptions which do not materially affect their validity in the present instance; they are summarized in Section 9. Tables derived from these expressions give values of ideal secondary-circuit loss as a multiple of W_C, the ideal secondary-circuit loss of a single-speed motor during acceleration from standstill to its synchronous speed against an inertia load; the ideal loss being that obtained when torques due to harmonics, stray loss and friction and windage are neglected. In addition, values are given for the sum of the secondary- and primary-circuit motor loss for a high-resistance-secondary machine having a ratio of equivalent secondary-to-primary resistance of 3 : 1, again as multiples of W_0 and also relative to the value obtained with regenerative braking of the dual-speed motor.

(4.1) Applications of Symmetrical Connections

(4.1.1) Dual-Speed Drives.

The availability of a speed as low as one-third full speed is advantageous in a number of industrial drives. For example, those applications where operation is normally at full speed, but a low speed is also required for accurate positioning, such as machine-tool, hoist and lift drives. Again, in the case of reciprocating pumps and axial-flow fans, the availability of one-third full speed facilitates economic operation during periods of low demand. Further, certain drives require two discrete speeds during each cycle of duty, such as a planing machine using a quick-return motion, automatic drilling and tapping machines using a slow feed and quick withdrawal, and tool-feed motions for which a quick traverse is occasionally required; i.e. applications where the lower speed is the working speed, but the

availability of a much higher speed is an economic advantage in increasing the rate of production of the finished article.

(4.1.2) **Frequent Start-Stop Drives.**

It is shown in Section 9.1 that, theoretically, the losses incurred during the starting operation of a 3 : 1 pole-changing motor may be reduced to about 55% of that incurred by a single-speed motor, in the case of an inertia load.

With regard to the stopping operation, where the time of retardation must be reduced to a minimum, regenerative braking may be used from full speed down to one-third speed, to reduce the kinetic energy of the drive to one-ninth of its initial value. This small residual energy may be readily removed by mechanical braking, with negligible wear of the brake. It may be noted that considerations of safety make it desirable, if not essential, to fit a mechanical brake to many industrial drives.

Alternatively, either d.c. dynamic braking or reverse connection to the a.c. supply—i.e. plugging—may be used. The former necessitates the extra expense and space requirements of a separate d.c. supply, whilst the latter necessitates special precautions against the possibility of reverse rotation of the drive. In both cases, braking to standstill can be attained without the use of mechanical brakes when the drive does not impose a torque on the motor at standstill.

It is shown in Section 9.2 that regenerative braking results in a much smaller energy dissipation in the motor circuits than either plugging or d.c. dynamic braking, the relative values being given in Table 1. Also, when the total heat dissipation due to regenerative and mechanical braking is of interest, it may be noted that the figure of 1·0 in Table 1 is increased by only some 6–12% (i.e. to 1·06 to 1·12) according as the primary resistance of the motor per phase is equal to, or small with respect to, the equivalent secondary resistance per phase.

Table 1

ENERGY DISSIPATED IN MOTOR CIRCUITS, WHILST BRAKING FROM FULL-SPEED TO STANDSTILL, EXCEPT IN THOSE INSTANCES MARKED *, FOR WHICH MECHANICAL BRAKES ARE USED BELOW ONE-THIRD SPEED

Braking method	3 : 1 Dual-speed motor		Single-speed motor		
	*Regenerative	Asymmetrical a.c.	*Zero-sequence	Plugging	D.C. dynamic
Secondary-circuit loss	$0{\cdot}44W_0$	$1{\cdot}7W_0$	$0{\cdot}64W_0$	$3W_0$	W_0
Secondary- plus primary-circuit loss	$0{\cdot}59W_0$	$2{\cdot}3W_0$	$0{\cdot}75W_0$	$4W_0$	$1{\cdot}3W_0$
Relative secondary- plus primary-circuit loss	1·0	3·9	1·3	6·9	2·3

It is shown in Section 9.3 that, again, when the complete start–stop cycle is considered, the use of a dual-speed motor for starting and regenerative braking results in a substantial reduction in the energy dissipated in the motor circuits. The values of energy dissipation in the single-speed motor, with alternative plugging and d.c. dynamic braking, are given in Table 2, together with the value for regenerative braking of the dual-speed motor.

For the complete start–stop cycle, the total energy taken from the supply mains is equal to the energy dissipated in the motor and the mechanical brake. However, the energy dissipated in the mechanical brake is only about 5% of the total energy and may therefore be neglected. Hence, the bottom row of Table 2 gives the relative energy costs of the different types of drive.

Table 2

ENERGY DISSIPATED IN MOTOR CIRCUITS PER START AND STOP CYCLE

Braking method	3 : 1 Dual-speed motor		Single-speed motor		
	*Regenerative	Asymmetrical a.c.	*Zero-sequence	Plugging	D.C. dynamic
Secondary-circuit loss	W_0	$2{\cdot}3W_0$	$1{\cdot}6W_0$	$4W_0$	$2W_0$
Secondary- plus primary-circuit loss	$1{\cdot}3W_0$	$3W_0$	$1{\cdot}9W_0$	$5{\cdot}3W_0$	$2{\cdot}7W_0$
Relative secondary- plus primary-circuit loss	1·0	2·3	1·4	4·0	2·0

* Methods require use of mechanical brakes for decelerating below one-third speed. Also, last two rows give energy input and relative energy input, respectively, from supply mains.

Thus, besides the possible reduction in the size of the motor, due to the reduced energy losses of the dual-speed machine, there is a substantial saving in operating costs. It may also be noted that in many start–stop drives the inertia of the rotor is the major part of the total inertia of the drive, and a decrease in the size of the rotor would therefore produce a still more favourable result with regard to operating costs than that shown by Table 2. Such observations apply equally to the duty cycle discussed in Section 4.1.3.

(4.1.3) **Frequently-Reversing Drives.**

It is shown in Section 9.4 that the energy loss incurred during each cycle of operation of a frequently-reversing drive may be calculated for various alternative methods of accelerating and decelerating the motor. The results are given in Table 3 for plugging, zero-sequence or d.c. dynamic braking in the case of a single-speed motor, and, in the case of a dual-speed motor, using regenerative braking from full to one-third speed, followed by plugging on the higher pole-number to one-third reverse speed, and motoring on the lower pole-number to full reverse speed.

Table 3

ENERGY DISSIPATED IN MOTOR PER REVERSAL CYCLE

Reversal method	3 : 1 Dual-speed motor	Single-speed motor		
	Regenerative braking, plugging on low speed and motoring on high speed	Zero-sequence braking and plugging	Plugging	D.C. braking and a.c. motoring
Secondary-circuit loss	$2{\cdot}7W_0$	$4{\cdot}8W_0$	$8W_0$	$4W_0$
Secondary- plus primary-circuit loss	$3{\cdot}6W_0$	$6{\cdot}2W_0$	$10{\cdot}7W_0$	$5{\cdot}3W_0$
Relative secondary- plus primary-circuit loss	1·0	1·7	3·0	1·5

Last two rows give energy input and relative energy input, respectively, from supply mains.

In the present instance, no mechanical braking is involved and Table 3 therefore also gives directly the relative total energy input from the supply mains per reversal cycle. Again, therefore, a great deal is gained by the use of a 3 : 1 dual-speed motor in preference to a single-speed motor.

It is well known that the positive- and negative-sequence admittances of an induction motor are of approximately equal magnitude at all speeds other than those close to the synchronous speed. It follows that the presence of a small negative-sequence component in the supply voltage results in only a small negative-sequence current, and a very small negative-sequence torque, relative to the positive-sequence quantities throughout more or less the whole of the speed reversal cycle. It is thus permissible to connect the 3-phase supply direct to the 2-phase triple-pole windings of the motor in either of the ways shown in Fig. 10. Positive- and negative-sequence 2-phase voltages of 96·5% and 26%, respectively, of the 3-phase line voltage are obtained in the case of Fig. 10(*a*), whilst values of 56% and 15%, respectively, are obtained in the case of Fig. 10(*b*); i.e. the magnitude of the negative-sequence voltage is 27% of that of the positive-sequence component in both cases.

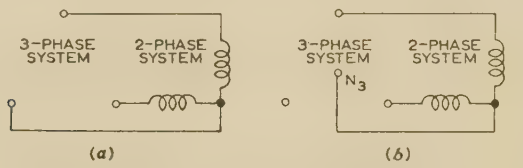


Fig. 10.—Unbalanced 2-phase supply obtained direct from the 3-phase supply.

(*a*) From 3-wire supply.
(*b*) From 4-wire supply.

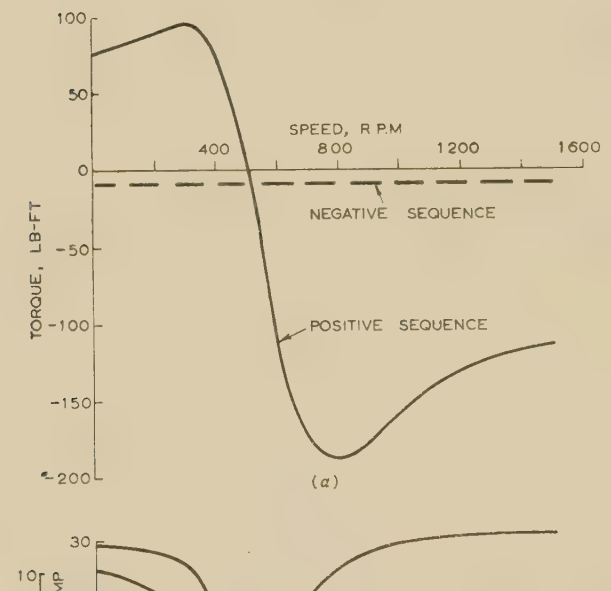


Fig. 11.—Characteristics of the experimental machine when operated from an asymmetric 2-phase supply obtained direct as in Fig. 10(*a*) from a 400-volt 3-phase supply.

(*a*) Torque/speed characteristics.
(*b*) Current/speed and power/speed characteristics.

Fig. 11 shows the positive- and negative-sequence torque, power and current characteristics of the experimental motor when operated from the asymmetrical 2-phase supply obtained as in Fig. 10(*a*). Evidently, the characteristics substantiate the validity of the above discussion.

Fig. 12 shows the connections of the motor and switching

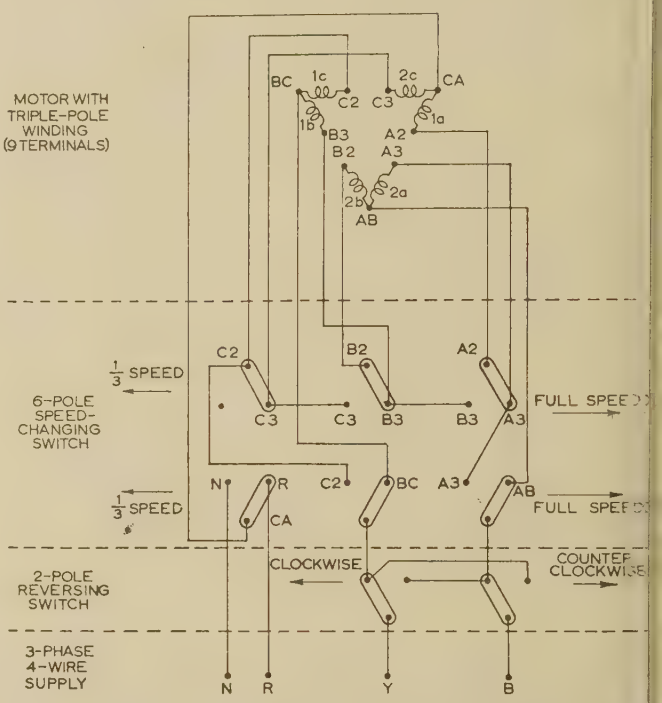


Fig. 12.—Switching scheme for a frequently-reversing drive using triple-pole steps.

arrangement as applied to an experimental plate-edge plan using available switchgear. It will be seen that the switchi arrangement is fairly simple, and two of the 3-phase lines pl the neutral wire are used for the supply of the 2-phase triple-po connection of the motor, as in Fig. 10(*b*). In this particular dri the triple-pole performance is of secondary importance co pared with that at full speed. Hence, standard high-spe laminations are used which, together with a fully-pitched sing layer primary winding, provide the optimum high-speed mo performance whilst enabling an economic reversal to be obtai with intermediate switching steps.

(4.2) Application of Asymmetrical Connections

The asymmetrical connections considered here will be restrict to those which give a.c. dynamic braking from full-speed standstill, or nearly standstill, without any tendency for t motor to run up in the reverse direction. Further, considerati will be restricted to those asymmetrical connections which prov some degree of regenerative braking. Thus, so far as the *p*-po winding is concerned, only the zero-sequence connection will considered.

(4.2.1) Zero-Sequence Connection.

The zero-sequence connection is obtained by connecting phases of a 3-phase machine in series, or in parallel, across

ingle-phase supply.[8] The zero-sequence torque/speed characteristic of the experimental machine is given in Fig. 13, using eries connection of the phases and a maximum permissible upply voltage of 500 volts, obtained via an auto-transformer rom the normal 400 volt supply. For comparison purposes, the ormal torque/speed characteristic is also included in Fig. 13.

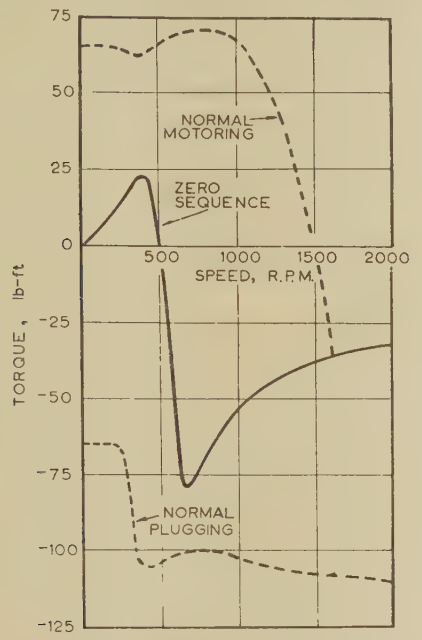


Fig. 13.—Zero-sequence torque/speed characteristic of the experimental machine at 167 volts per phase compared with the normal motoring and plugging characteristics at 400 volts per phase.

It will be seen that a substantial braking torque is obtained from full speed down to one-third of full speed, and that an appreciable motoring torque is available below one-third speed. Above one-third speed, a regenerative braking torque arises from the forward rotating component of the single-phase $3p$-pole field, plus a plugging torque arising from the backward rotating component of the field. In consequence, this type of braking is attractive from the point of view of motor heating, the energy dissipated in the motor circuits being only 22% of that for plugging to standstill from full speed, and 65% of that for d.c. dynamic braking (see Table 1 and Section 9.2). As mentioned in Section 4.1.2, mechanical braking may be used from one-third speed to standstill to dissipate the remaining 11% of the initial kinetic energy.

(4.2.2) Asymmetrical Triple-Pole Connection

The asymmetrical connections which are most effective in providing a.c. dynamic braking down to standstill, without any tendency for reverse rotation, are those which produce equal positive- and negative-sequence voltage components. Fig. 14

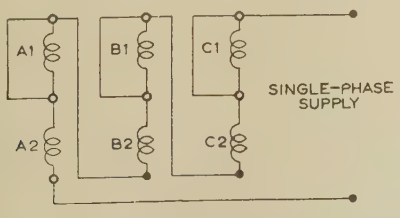


Fig. 14.—$3p$-pole connection for equal positive- and negative-sequence voltage components.

o Terminals.

illustrates a connection of the 2-phase triple-pole winding which produces equal positive- and negative-sequence voltage components of 50% of the line voltage.[5] A corresponding connection of the 3-phase triple-pole winding exists, but does not appear to be of practical value since an excessive number of motor terminals is required.

It should be noted that it is necessary to use an equivalent triple-pole secondary resistance which is at least numerically equal to, and preferably greater than, the total triple-pole leakage reactance of the motor (i.e. peak torque should occur at a slip $\geqslant 1{\cdot}0$) if a.c. dynamic braking is to be effective down to standstill; i.e. if it is desired to avoid the use of a mechanical brake. Fig. 15 illustrates the torque/speed characteristics of the experimental machine for the connection of Fig. 14, and with varying ratios of equivalent triple-pole secondary resistance to total triple-pole leakage reactance. Evidently, by suitable choice of the ratio, a gentle braking torque can be obtained at low speeds, in contrast with d.c. dynamic braking. It has been pointed out by Noodleman[3] that this is a distinct advantage in many machine-tool drives.

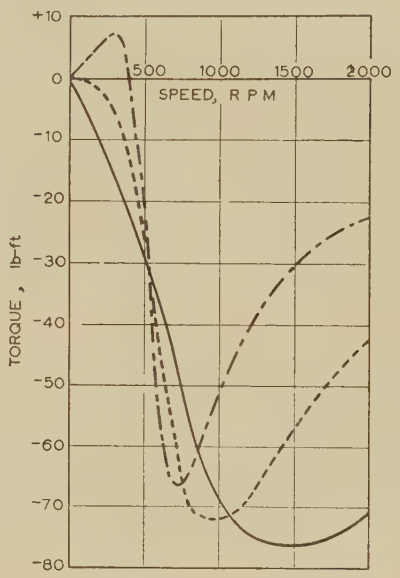


Fig. 15.—Predicted torque/speed characteristics for the experimental machine with different values of secondary resistance and connected as in Fig. 14 to a 400-volt supply.

—·— $R_2 = 0{\cdot}5(X_1 + X_2)$
— — — $R_2 = 1{\cdot}0(X_1 + X_2)$
——— $R_2 = 2{\cdot}0(X_1 + X_2)$

It is shown in Section 9.2 that the energy dissipation in the motor circuits with a.c. dynamic braking (i.e. using the asymmetrical triple-pole connection) can be calculated, and the results are included in Tables 1 and 2 under the heading of "asymmetrical a.c." Evidently this method of braking is likely to be preferred for many applications, since there is no danger of reverse rotation of the motor, the expense and space requirements of a separate d.c. supply are avoided, and so too is the use of a mechanical brake.

It may be noted that although a satisfactory braking and overall performance can be obtained with a high-resistance single-cage rotor, the use of the unconventional brushless rotor of Section 3.1, or the single-winding rotor circuit of Fig. 9, allows a greater freedom in obtaining the best overall motoring and braking performance.

Obviously, the single-winding rotor circuit of Fig. 9 is a most desirable arrangement in that the external resistances may be

preset for the best accelerating and braking performance, thereby minimizing the control equipment and dissipating the major part of the energy loss external to the motor.

(5) COMPARISON OF 3 : 1 AND 2 : 1 SINGLE-WINDING POLE-CHANGING INDUCTION MOTORS

The 3 : 1 and 2 : 1 single-winding pole-changing motors are not in general directly competitive for constant-speed applications. However, they are directly competitive for the applications discussed in Section 4.1.2 *et seq.* Before comparing their relative merits for such applications, their effectiveness in utilizing a given frame size of machine will be compared.

(5.1) Relative Performance for Given Frame Size

The comparison is based upon equal power output at the same top speed. The 2 : 1 motor is assumed to have a winding spread of 60° and a pitch of approximately 60% at the higher speed, and a 120° spread and approximately 120% pitch at the lower speed. The windings are delta-connected for low-speed operation and star-connected (two parallel circuits) for high-speed operation. This is representative of modern practice in obtaining the best overall performance. The 3 : 1 motor is assumed to have a full-pitch winding at both speeds, with 60° spread 3-phase at the higher speed, and 90° spread 2-phase at the lower speed.

The primary winding factor of the 2 : 1 motor is 0·772 for the high-speed connection and 0·786 for the low-speed connection, whilst the corresponding values for the 3 : 1 motor are 0·955 and 0·9. Since the utilization of the winding space varies as the square of the winding factor, the 2 : 1 winding is 65% and 68% effective, respectively, whilst the 3 : 1 winding is 100% and 89% effective, respectively, relative to a full-pitched winding of 60° phase-spread. Furthermore, a single-layer winding can be used for the 3 : 1 motor to obtain the best possible copper space-factor in the slots.

The 3 : 1 winding has, of course, the disadvantage of a rather greater overhang length. However, although this may increase the primary resistance beyond the ideal for a single-speed winding for the lower speed, it does not necessitate any derating of the motor because the heat capacity and heat dissipating surface of the winding have increased proportionately.

It will be appreciated, from the foregoing discussion, that with the 2 : 1 winding a considerable amount of derating is necessary below the maximum output obtainable from single-speed motors of the same frame size. Such derating is the result of the need for a compromise magnetic circuit as well as a reduced utilization of the primary winding space, as discussed above. In practice only about 60–70% of the maximum respective single-speed outputs for a given frame size can be obtained with a 2 : 1 single-winding motor. On the other hand, the 3 : 1 single-winding motor requires to be derated only on account of the need for a compromise magnetic circuit, and it is usually possible to obtain about 80–90% of the maximum respective single-speed outputs.

It may be noted, also, that in the case of a 3 : 1 pole-changing motor using two separate primary windings, only about 45–60% of the maximum single-speed outputs can be obtained. It can therefore be seen that the 3 : 1 single-winding pole-changing connections enable the size of the motor to be kept to a minimum and may, in some cases, not require an increase in the frame size compared even with single-speed motors. The reduced space requirements, material and labour costs, and motor inertia, compared with both 3 : 1 dual-winding and 2 : 1 single-winding motors, are distinct advantages of the 3 : 1 single-winding machines which may, in many cases, more than balance the need for an auxiliary transformer and more elaborate control-gear.

(5.2) Relative Performance on Prescribed Duty Cycle

As noted in Section 4, the energy dissipation in the motor po duty cycle becomes the most important consideration whe operating with continuously changing speed.

It is shown in Section 9 that the energy dissipation may b readily calculated for a 3 : 1 or a 2 : 1 motor, when the load ca be represented by an equivalent inertia at the motor shaft—a example of such a load being a centrifuge. It should be born in mind that even when the load is represented by an equivale inertia and a torque, as with a hoist or a planing machine, th energy dissipation due to the inertia is still most important ar a comparison of the 3 : 1 and 2 : 1 motors on the basis of a inertia load is of value. Evidently, with a load combining inert and torque it is particularly advantageous to use the machin capable of giving the maximum possible torque/inertia ratio reduce the cycle time, and thereby the total energy consumptio i.e. the 3 : 1 motor is preferable to the 2 : 1 motor.

(5.2.1) Start-Stop Cycle.

When operating on a start–stop duty with 2-speed acceler tion, followed by regenerative braking to the lower synchrono speed, the energy dissipated in the 2 : 1 motor circuits is abo 10% less than in the 3 : 1 machine, but the residual kinetic ener at the lower speed is 2·25 times as great. Thus, when th customary method of mechanical braking is used to dissipa the residual energy, the brakes must be proportioned for th much greater duty in the case of the 2 : 1 motor, or a far great rate of wear must be accepted. Alternatively, when the resid energy is dissipated by plugging on the lower-speed connectio the total energy dissipated in the 2 : 1 motor circuits is 12 greater than in the 3 : 1 machine.

When a.c. dynamic braking is used from full speed to stan still, with an asymmetrical connection of the primary windin producing equal positive- and negative-sequence voltage com ponents, as discussed in Section 4.2.2, the energy dissipated the 2 : 1 motor is about 35% greater than in the 3 : 1 machi for the complete start–stop cycle.

(5.2.2) Reversal Cycle.

When operating on a reversal duty with regenerative brakin to the lower speed, followed by plugging to the reverse low speed, and motoring to the reverse full speed, the energy co sumption per cycle with the 2 : 1 motor is about 12% great than with the 3 : 1 machine.

(5.3) Inching Duty and Low-Speed Control

Evidently, since the 3 : 1 motor has an appreciably low synchronous speed than the 2 : 1 machine, an inching duty c be carried out with the former motor at a greater electric efficiency and with a greater degree of mechanical control of t load. Similarly, when speed control by variable seconda resistance is utilized, a more stable and efficient low speed c be attained with the 3 : 1 motor than with the 2 : 1 machine.

(5.4) Auxiliary Apparatus and Motor Windings

Both machines require that each phase be divided into t similar parts, so that the direct costs of winding should not significantly different. In general, however, nine terminals a required for the 3 : 1 motor as against six for the 2 : 1 machi

The 2 : 1 motor requires a 6-pole switch, three poles of whi must be double-throw. The 3 : 1 machine requires an 8-po double-throw switch and a small auto-transformer, as discuss in Section 2.2, when continuous operation at the lower speed required. However, the transformer rating is about one-si of the full-speed rating of the motor, so that its size and co are relatively small.

(6) CONCLUSIONS

The single-winding pole-changing motor is obviously preferable to the dual-winding type for reasons of economy and space requirements. Hitherto, in limiting the necessary number of motor terminals and complication of the control equipment, the application of single-winding motors has been more or less restricted to drives of 2 : 1 speed ratio. It is shown that a motor of 3 : 1 speed ratio is available, with little increase in the number of motor terminals and complication of the control equipment.

The latter machine overlaps and extends the sphere of application of the former, since it permits (*a*) a larger range of regenerative braking to reduce considerably the wear on mechanical brakes, (*b*) a similar reduction in motor heating during acceleration to the higher speed, and during reversal at the higher speed, (*c*) a lower economic running speed, and (*d*) a more efficient method of asymmetrical a.c. dynamic braking from full speed to standstill.

The efficiency of the asymmetrical a.c. method of dynamic braking on the triple-pole connection is comparable with that of d.c. dynamic braking and may be preferred for many applications, since the expense and space requirements of a separate d.c. supply are avoided. Also, in contrast with plugging, there is no danger of reverse rotation of the motor. Such applications are cited by Noodleman[9] as including (i) drill presses or milling machines, to provide rapid stopping for the changing of tools, to avoid damage of the work, and to facilitate the transfer of gears, (ii) lathes requiring a gentle stop to minimize the occurrence of loose chucks and of twisting heavy shafts, (iii) headstock drive on universal grinders, for rapid braking and inching operations, and (iv) special drives for automatic drilling, tapping, armature winding, and the positioning of jig borers.

Further, the winding utilization of the 3 : 1 pole-changing motor is appreciably better than that of the 2 : 1 motor and requires considerably less derating of a given frame size. Thus, the characteristics of the 3 : 1 motor are more nearly identical with those which can be obtained from two single-speed motors of the same frame size.

The ability of the 3 : 1 motor to provide a satisfactory accelerating and braking performance is of interest in applications where a large inertia is involved, such as the centrifuges used in sugar refineries and laundries.

The availability of the one-third speed is advantageous for applications where operation is normally at full speed, but a low speed is also required for accurate positioning, such as machine tool, hoist and lift drives; where a low speed is required for appreciable periods of time, as in the case of reciprocating pumps and axial-flow fans, to facilitate economical operation during periods of low demand; and where operation is normally at the lower speed, as in the case of a planing machine and various tool feed motions, but a much higher speed is required for the quick-return motion or quick traverse.

(7) ACKNOWLEDGMENTS

The facilities provided by the University of Sheffield, and the concurrence of Lancashire Dynamo and Crypto Ltd., in the publication of the paper, are gladly acknowledged.

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(9) APPENDICES—ENERGY DISSIPATION IN INDUCTION MOTOR CIRCUITS

The rate of energy dissipation, in watts, occurring in the secondary circuit of an induction motor producing a torque of T lb-ft at a fractional slip of s is

$$P = \frac{2\pi \times 746}{33\,000} N_s T s = 0{\cdot}142 N_s T s \quad . \quad . \quad . \quad (1)$$

where N_s is the synchronous speed of the motor in revolutions per minute.

Hence, the energy dissipated, in joules, in the secondary circuit when the slip changes from s_1 to s_2 during the interval of time t_1 to t_2, is

$$W' = \int_{t_1}^{t_2} 0{\cdot}142 N_s T s dt \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In the particular case of an inertia or "dead" load, having an equivalent moment of inertia I lb-ft^2 at the motor shaft, and when torques due to friction and windage, harmonics and stray losses are neglected,

$$T = \frac{2\pi}{60g} I \frac{dN}{dt} = 0{\cdot}00325 I \frac{dN}{dt} \quad . \quad . \quad . \quad (3)$$

where N is the actual speed of the motor at any instant and is given by

$$N = N_s(1 - s)$$

Thus

$$\frac{dN}{dt} = -N_s \frac{ds}{dt}$$

and, by substitution in eqn. (3),

$$T dt = -0{\cdot}00325 I N_s ds \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Hence, from eqns. (4) and (2),

$$W' = -0{\cdot}00046 I N_s^2 \int_{s_1}^{s_2} s ds$$

i.e.

$$W' = k N_s^2 (s_1^2 - s_2^2) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where $k = 230I \times 10^{-6}$. Evidently, eqn. (5) expresses the loss in the more practical units of watt-minutes when the constant k is reduced to $3{\cdot}81I \times 10^{-6}$.

The particular value of W' when $s_1 = 1$ and $s_2 = 0$ (i.e. when the induction motor is accelerated from standstill to full speed) is

$$W_0 = k N_s^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (5a)$$

and, since the effect of torques due to friction, windage, harmonics and stray loss are neglected, it is termed the "ideal" secondary-circuit loss.

It will be seen, from the well-known equivalent circuit of the induction motor, that when the primary circuit is connected to an a.c. supply and the magnetizing current is neglected, the total energy dissipated in the motor circuits, in joules, is

$$W = (1 + R_1/R_2)W'$$

i.e. $$W = kN_s^2(1 + R_1/R_2)(s_1^2 - s_2^2) \quad . \quad . \quad . \quad . \quad (6)$$

where R_1 is the resistance of the primary winding per phase, and R_2 is the resistance of the secondary winding referred to the primary winding per phase, in ohms.

Similarly, it can be shown that the total energy dissipated, in joules, in the motor circuits when d.c. dynamic braking is used to reduce the speed from N_1 to N_2 r.p.m. is

$$W = k(N_1^2 - N_2^2)(1 + R_1/R_2) \quad . \quad . \quad . \quad . \quad (7)$$

when the magnetizing reactance of the primary winding is large compared with the values of $\sqrt{(2R_1R_2)}$ and the equivalent leakage reactance of the secondary winding.

Also, when an a.c. supply is connected to an asymmetrical arrangement of the primary windings to provide equal positive- and negative-sequence phase voltages of the motor, and the value of R_2 is greater than the total equivalent leakage reactance of the motor to give braking down to standstill, it can be shown that the total energy dissipated, in joules, in the motor circuits may be taken as

$$W = kN_s^2\left[(s_1^2 - s_2^2) + 2(s_2 - s_1) + 2\log_e\frac{1 - s_1}{1 - s_2}\right](1 + R_1/R_2) \quad . \quad . \quad . \quad . \quad (8)$$

The above form of braking may be referred to as the asymmetrical a.c. method.

Again, when the zero-sequence connection of the primary windings is used for braking at speeds greater than one-third of the synchronous speed, it can be shown that the total energy dissipated in the motor circuits, in joules, may be taken as

$$W = \frac{kN_s^2}{9}\left[(s_1^2 - s_2^2) - 2(s_1 - s_2) + 2\log_e\frac{1 - s_2}{1 - s_1}\right](1 + R_1/2R_2) \quad . \quad . \quad . \quad . \quad (9)$$

where the slips, s_1 and s_2, are referred to the zero-sequence synchronous speed of $N_s/3$.

It may be noted that, in deriving eqns. (8) and (9), it has been assumed that the secondary resistance is independent of frequency. This assumption involves little error in the case of high-resistance squirrel-cage and slip-ring rotors.

(9.1) Starting of Single-Speed and 3 : 1 Dual-Speed Motors

In accelerating from standstill ($s_1 = 1{\cdot}0$) to full speed ($s_2 \simeq 0$) in the case of a single-speed p-pole motor, the energy dissipated in the motor circuits is, from eqn. (6),

$$W_1 = kN_s^2(1 + R_1/R_2) \quad . \quad . \quad . \quad . \quad (10)$$

In accelerating as a $3p$-pole motor from standstill to full speed (approximately $N_s/3$), the energy dissipated in the motor circuits is, from eqn. (10),

$$W_2 = k(N_s/3)^2(1 + R_1/R_2) = W_1/9 \quad . \quad . \quad . \quad (11)$$

Further, in accelerating as a p-pole motor from a speed of $N_s/3$, i.e. a slip of $s_1 = 2/3$, to full speed ($s_2 \simeq 0$), the energy dissipated in the motor circuits is, from eqn. (6),

$$W_3 = kN_s^2(1 + R_1/R_2)(2/3)^2 = 4W_1/9 \quad . \quad . \quad (12)$$

Hence, in accelerating as a dual-speed motor from standstill to the full speed of approximately N_s, the energy dissipated in the motor circuits is, from eqns. (11) and (12),

$$W_4 = 5W_1/9 \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

That is, the energy dissipated in the circuits of a dual-speed motor in accelerating from standstill to the full speed, of approximately N_s, is 55·5% of that for a single-speed motor.

(9.2) Stopping of Single-Speed and 3 : 1 Dual-Speed Motors

When the method of plugging or reverse connection is used to decelerate a single-speed p-pole motor from near synchronous speed ($s_1 \simeq 2$) to standstill ($s_2 = 1$), the energy dissipated in the motor circuits is, from eqn. (6),

$$W_5 = kN_s^2(1 + R_1/R_2)(4 - 1) = 3W_1 \quad . \quad . \quad (14)$$

For the same speed range with d.c. dynamic braking, the energy dissipated in the motor circuits is, from eqn. (7),

$$W_6 = kN_s^2(1 + R_1/R_2) = W_1 \quad . \quad . \quad . \quad (15)$$

In the case of the asymmetrical a.c. method of braking, the energy dissipated in the motor circuits increases indefinitely as the speed approaches zero, in the hypothetical case of negligible frictional torque. It can be safely assumed that the braking effect of the frictional torque is sufficient to bring the motor to standstill when the disconnection of the a.c. supply is delayed until the speed falls to 4% of full speed. Thus, the energy dissipated in the circuits of the dual-speed motor, operating on the larger pole-number, may be taken, from eqn. (8), as

$$W_7 = kN_s^2(3{\cdot}23 + 5{\cdot}76 + 2\log_e 25)(1 + R_1/R_2)/9$$

i.e. $$W_7 = 1{\cdot}7kN_s^2(1 + R_1/R_2) = 1{\cdot}7W_1 \quad . \quad . \quad . \quad (16)$$

In the case of zero-sequence braking of a single-speed motor from full speed to one-third speed, the energy dissipated in the motor circuits is, from eqn. (9),

$$W_8 = kN_s^2(4 + 4 + 2\log_e 0{\cdot}333)(1 + R_1/R_2)/9$$

i.e. $$W_8 = 0{\cdot}64(1 + R_1/2R_2)W_1/(1 + R_1/R_2) \quad . \quad . \quad (17)$$

Similarly, in the case of regenerative braking with the 3 pole-changing motor from the higher to the lower synchronous speed, the energy dissipated in the motor circuits is, from eqns. (6) and (10),

$$W_9 = 4W_1/9 \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Thus, assuming that the residual kinetic energy of one-ninth its initial value is dissipated in mechanical braking, when the regenerative and zero-sequence methods are utilized, the relative energy dissipated in the circuits of a high-resistance type of induction motor ($R_2/R_1 = 3$, say), with alternative methods of braking from full speed to standstill, have been calculated from eqns. (14)–(18) and are shown in Table 1.

It may be noted that a high-resistance type of motor has been considered since it is customarily used for frequent start-stop drives to obtain high braking and starting torques, and to reduce the energy dissipated in the motor circuits.

(9.3) Combined Start-Stop Cycle of Single-Speed and 3 : 1 Dual-Speed Motors

The start-stop cycle of a single-speed motor has an energy dissipation in the motor circuits expressed by eqn. (10) plus that expressed either by eqns. (14) and (15), or by eqn. (17), according as plugging, d.c. dynamic braking, or zero-sequence braking

used, respectively. Similarly, eqn. (13) and either eqn. (16) or eqn. (18) are used for asymmetrical a.c. or regenerative braking, respectively, in the case of a 3 : 1 dual-speed motor. Thus, the relative energy dissipations in the circuits of a high-resistance type of induction motor ($R_2/R_1 = 3$), per start- and stop-cycle, may be shown as in Table 2.

(9.4) Reversal Cycle of Single and 3 : 1 Dual-Speed Motors

In the case of a single-speed motor, the energy dissipated in the motor circuits in changing from full speed forward to full speed backward by the method of plugging is, from eqns. (14) and (10),

$$W_9 = 3W_1 + W_1 = 4W_1 \quad . \quad . \quad . \quad . \quad (19)$$

When d.c. braking is used from full speed forward to approximately standstill, followed by motoring to full speed backward, the energy dissipated in the motor circuits is, from eqns. (15) and (10),

$$W_{10} = W_1 + W_1 = 2W_1 \quad . \quad . \quad . \quad . \quad (20)$$

When zero-sequence braking is used from full speed forward to approximately one-third speed forward, followed by plugging to full speed backward, the energy dissipated in the motor circuits is, from eqns. (17) and (6),

$$W_{11} = 0{\cdot}6W_1 + 1{\cdot}6W_1 = 2{\cdot}2W_1 \quad . \quad . \quad . \quad (21)$$

in the case of a high-resistance type of rotor (i.e. $R_2/R_1 = 3$).

In the case of the 3 : 1 dual-speed motor, when regenerative braking is used from the higher to the lower synchronous speed forward, followed by plugging on the higher pole-number winding to the lower synchronous speed backward, and acceleration on the lower pole-number to full-speed backward, the energy dissipated in the motor circuits is, from eqns. (18), (14) and (13),

$$W_{12} = W_9 + W_5/9 + W_4 = 12W_1/9 \quad . \quad . \quad . \quad (22)$$

Thus, the relative energy dissipations in the circuits of the motor, per reversal cycle, may be shown as in Table 3.

[The discussion on the above paper will be found on page 316.]

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THE DEVELOPMENT OF A NEW 3 : 1 POLE-CHANGING MOTOR

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(*The paper was first received* 19*th July, and in revised form* 30*th September*, 1955. *It was published in December*, 1955, *and was read before the* UTILIZATION SECTION 16*th February*, 1956.)

SUMMARY

The paper describes the development of a new 3 : 1 pole-changing induction motor with one 3-phase winding only, in which the performance and rating of a given machine frame for each speed are in all respects nearly equal to the best values that could be obtained from the same frame if it were wound in a normal manner for that speed only. The comparison is equally favourable both for torque ratings and for continuous horse-power ratings, and the machine is free from the crawling torques common in pole-changing motors. The number of control leads (eleven) is not unduly large, and the switch controller required is relatively simple.

A simple pole-changing winding which gives a high performance for a 2 : 1 speed ratio is well known and widely used, and it seems probable that the development of a winding giving even better performance for a 3 : 1 speed ratio will find many applications, once its existence is generally known. It is believed that this is the first time a satisfactory winding of this type has been devised, although several comparable but unsatisfactory variants have previously been proposed.

LIST OF PRINCIPAL SYMBOLS

T_m = Peak number of magnetizing turns acting on pole centre.
h_1 = Peak magnetomotive force for current vector position I, AT/pole.
h_2 = Peak m.m.f., for current vector position II, AT/pole.
n = Number of conductors per pole per phase in the complete winding for the lower number of poles.
I_a = Current (r.m.s.) per phase, amp.
I = Peak current per phase, amp.
θ = Electrical angle, rad.
m = Order of harmonic.

(1) INTRODUCTION

In a companion paper,[1] one of the authors has described various theoretical aspects of zero-sequence and 3rd-harmonic fields. The present paper discusses the application of this theory in what is believed to be the first satisfactory 3 : 1 pole-changing winding,[2] using only one winding for both speeds. The theoretical principle of pole-tripling is well known,[3,4] and there have been various attempts[4,5] at producing a winding to use this effect, but the results have all suffered from one defect or another, in particular from crawling torques[5] or from a low rating, for the particular machine frame, at one or other of the two speeds.

The machine here described has been proved by full tests to be thoroughly satisfactory in operation, being almost immune from the usual defects of pole-changing machines, and giving very nearly the full frame rating for both speeds. In the course of the development of the machine to its final form, a number of interesting theoretical and practical points arose and they are discussed in some detail in the paper.

(2) PROTOTYPE POLE-TRIPLING ARRANGEMENT

Several previous papers[1,3,4,5,6] have discussed pole-tripling effects, some of them in considerable detail. In brief, if an alternating voltage is applied at one corner of an open-delta connected 3-phase winding, a pulsating field is set up having three times as many poles as the normal for the delta winding. If the rotor of a squirrel-cage machine, in which there exists such a pulsating field, is given an initial start, the machine will run as a single-phase induction motor at a speed corresponding to three times the normal number of poles, i.e. at one-third the normal speed. There are, however, obvious objections to the use of such a scheme for pole-changing. It is single-phase; has no self-starting torque; it has an m.m.f. wave of inferior shape; and the permissible applied single-phase voltage is about two-thirds of the normal line voltage of the machine. Fig. 1 shows the m.m.f. waveform for a series-connected 3-phase winding having one, two or three slots per pole per phase, and it will be seen that, at best, it has a very large harmonic content.

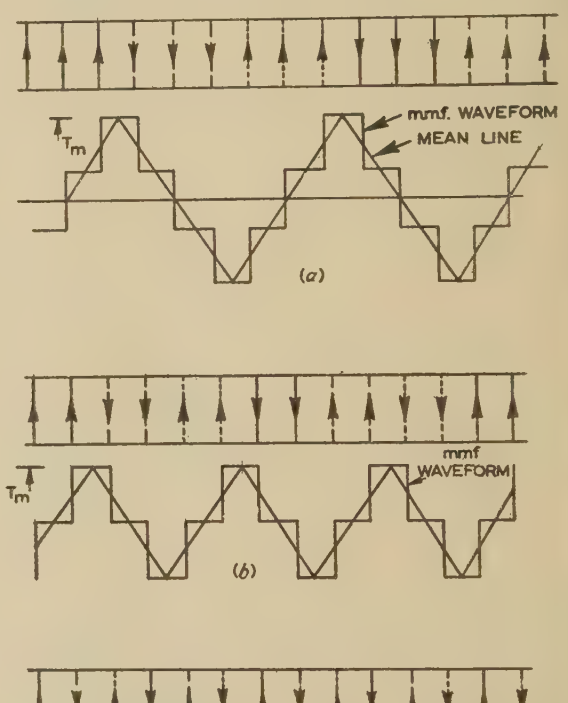


Fig. 1.—Distribution of turns and m.m.f. of 3-phase full-pitch winding, series-connected.

(*a*) 3 slots/pole/phase. $y = \frac{8T_m}{3\pi}\left(\sin\theta - \frac{1}{2\times 3}\sin 3\theta + \frac{1}{5}\sin 5\theta + \ldots\right)$

(*b*) 2 slots/pole/phase. $y = \frac{2\sqrt{2}T_m}{\pi}\left(\sin\theta - \frac{1}{3}\sin 3\theta - \frac{1}{5}\sin 5\theta + \frac{1}{7}\sin 7\theta + \ldots\right)$

(*c*) 1 slot/pole/phase $y = \frac{4T_m}{\pi}\left(\sin\theta + \frac{1}{3}\sin 3\theta + \frac{1}{5}\sin 5\theta + \ldots\right)$

Prof. Rawcliffe is Professor of Electrical Engineering, University of Bristol. Mr. Jayawant is in the Electrical Engineering Department of the University.

A delta winding fed at one opened corner is, of course, series-connected, in the sense that the voltage is applied to the three phases connected in series in the same direction.

(3) FIRST MODIFICATION: USE OF FULL WINDING

To meet these objections and in the effort to develop a satisfactory 3 : 1 pole-changing winding, the winding arrangements shown in Figs. 2 and 3, together with the corresponding current vectors and m.m.f. waveforms, were studied. The "mean lines" shown represent the limiting values of m.m.f. produced when the number of slots is large. The winding is shown in Figs. 2 and 3 as a single layer, but a double-layer winding, which is the preferred arrangement in practice, was used throughout the tests. As is well known, for a full-pitch 60°-spread winding only, the lower layer duplicates the upper layer, and the waveforms and circuit connections are unaltered by the change from single layer to double layer.

In effect, the whole winding was divided into nine phase bands ($A_1B_1C_1 : A_2B_2C_2 : A_3B_3C_3$) instead of three. This involved 18 leads out—a rather large number for commercial use. Phases A_1, B_1 and C_1, taken together, form a standard 2-pole 3-phase winding, except that the phase spread is only 20°. Phases A_2, B_2 and C_2 similarly form another 2-pole 3-phase winding, as also do phases A_3, B_3 and C_3. Each of these 2-pole 3-phase windings can be connected in series to give one single-phase winding with three times as many poles, as explained above. The spread of each resultant winding with respect to the larger number of poles is, of course, 60°.

Since the spacing $A_1 \rightarrow A_2 \rightarrow A_3$ is 40° with respect to the lower number of poles, it is 120° with respect to the triple-pole system, and the three resultant single-phase windings, taken together, thus form a 3-phase winding with three times the fundamental number of poles. If, however, phase bands $(+A_1, -B_3 + A_2)$, $(+B_1 - C_3 + B_2)$ and $(+C_1 - A_3 + C_2)$ are connected in series, respectively, each of these groups becomes

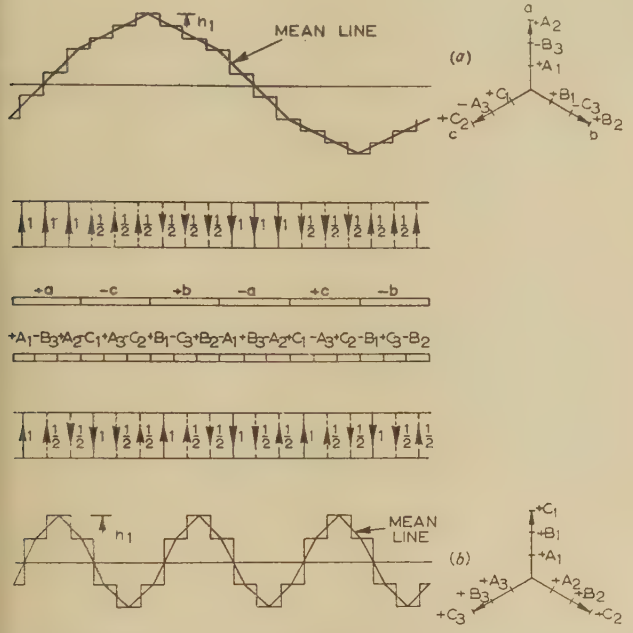


Fig. 2.—Prototype 3 : 1 pole-changing winding. 60° spread; vector position I.

(*a*) M.M.F. diagram and vector diagram with phase bands for 2 poles.
(*b*) M.M.F. diagram and vector diagram with phase bands for 6 poles.

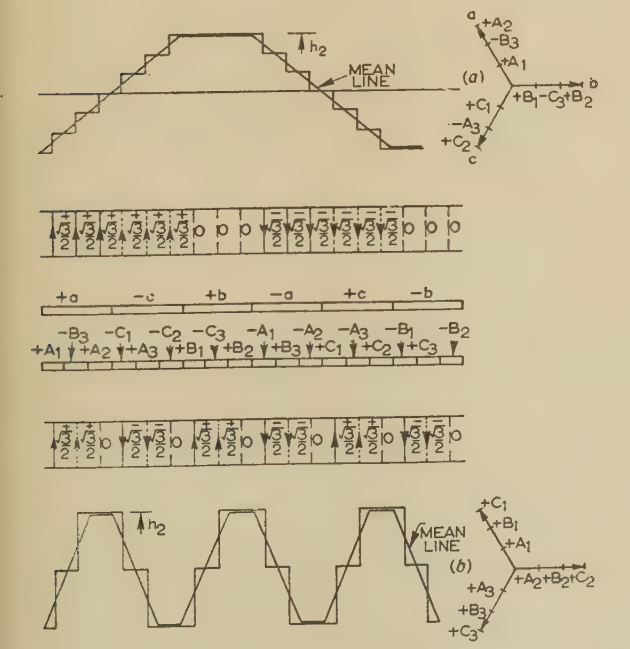


Fig. 3.—Prototype 3 : 1 pole-changing winding: 60° spread: vector position II.

(*a*) M.M.F. diagram and vector diagram with phase bands for 2 poles.
(*b*) M.M.F. diagram and vector diagram with phase bands for 6 poles.

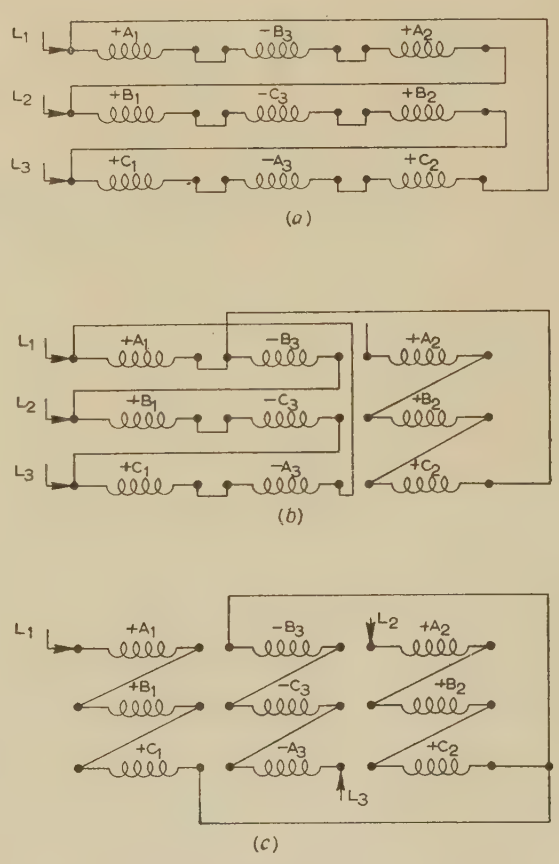


Fig. 4.—3 : 1 pole-changing winding. 60° spread.

(*a*) Prototype winding. Connections for high-speed running. Full winding used. 18 leads.
(*b*) Modified winding. Connections for high-speed running. Two-thirds of winding used. 13 leads. A_2, B_2 and C_2 carry no current.
(*c*) Modified winding. Connections for low-speed running. 13 leads.

one phase of a normal 60°-spread winding, and a normal 3-phase winding for the lower pole number is produced. The connections of the nine phase bands for the two numbers of poles are shown in Figs. 4(*a*) and 4(*c*). As will be seen by reference to Figs. 2 and 3, the resultant winding is a full-pitch 60°-spread winding with respect to both pole numbers, and the m.m.f. waves are the ideal 3-phase shapes in all cases.

The drawback of this winding, however, apart from the fact that 18 external leads are required, is the low flux density at the higher speed. Since the number of conductors per phase is the same for each connection, the flux density at the higher speed will be only one-third that at the lower speed, for star connection in both cases.

Although this connection is shown by Richter,[3] it has no commercial use in this form. A very considerable improvement is, however, produced by delta connection at the higher speed, although even this gives only about $1/\sqrt{3}$ of the full flux and is therefore inefficient in torque rating. This might be no disadvantage in certain applications.

(4) SECOND MODIFICATION: USE OF PART OF WINDING AND 60° SPREAD

(4.1) Omission of One-third of Winding at the Higher Speed

It was then decided to omit one-third of the winding at the higher speed, connecting each 60° phase band either with a 20° gap unwound in the centre, or with a 40° section wound continuously, followed by a 20° gap. This reduction to two-thirds of the number of conductors increases the flux almost to normal. It is always possible so to reduce the conductors, since it is, of course, necessary to have 3 slots per pole per phase (or 6 or 9 or higher multiple) in the original winding if 3 : 1 pole changing is to be possible at all.

To leave one-third of the winding out of commission at the higher speed may at first appear uneconomic, and in some senses it is, but only when judged against the theoretically perfect standard of 100% rating and performance at both speeds. Indeed, the optimum design of a 4-pole winding in a given frame will have less copper in it than a 12-pole winding for the same frame. But compared with 2 : 1 pole-changing windings, which have won wide acceptance, this 3 : 1 winding is certainly better; for example, it is effectively full-pitched for both numbers of poles, whereas the common 2 : 1 pole-changing winding has a chord factor of 0·707 at one speed, which in itself is nearly equivalent to wasting one-third of the total turns.

The 20° sections excluded from each phase at the higher speed form one complete phase at the lower speed, and since it is now intended only to use them at the lower speed they can be permanently connected in series as shown in Figs. 4(*b*) and 4(*c*). They could be wound with coils of pitch equal to one pole pitch of the greater number of poles. This would economize copper and increase both efficiency and rating, and it might reduce the leakage reactance due to end windings, though this is not certain, since much end-winding leakage is cancelled by mutual inductance between phases. This short-pitched variant has not been tested; it necessarily involves a more difficult winding in which two kinds of coil are used, but the possibility should be recorded. The basic method of using only two-thirds of each phase at the higher speed is shown in Fig. 4(*b*), where 13 leads are seen to be necessary, but it is possible further to reduce the number of leads to 9 by using some of the interphase connections for the higher speed also as series connectors for the lower speed. This reconnection is shown in Fig. 5, and the simple 6-gang switch needed to act as switch-controller for this pole-changing winding is shown in Fig. 6(*a*). The numerical marking of the two Figures is the same.

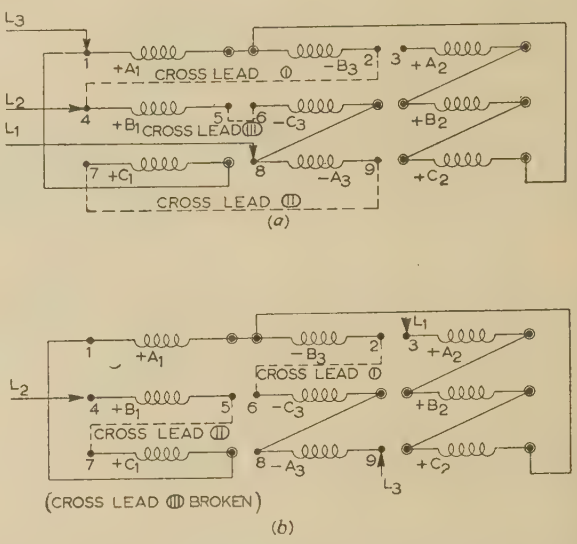


Fig. 5.—3 : 1 pole-changing winding, 60° spread, with connection modified to reduce number of leads to nine.

(*a*) Connections for high-speed running. A_2, B_2 and C_2 carry no current.
(*b*) Connections for low-speed running.

Continuous lines indicate fixed connections; broken lines indicate switch connections.
In prototype, 18 leads were brought to terminals.
9 terminals shown thus ⊙ can be fixed connections.
9 terminals shown thus ● must be brought out to leads.

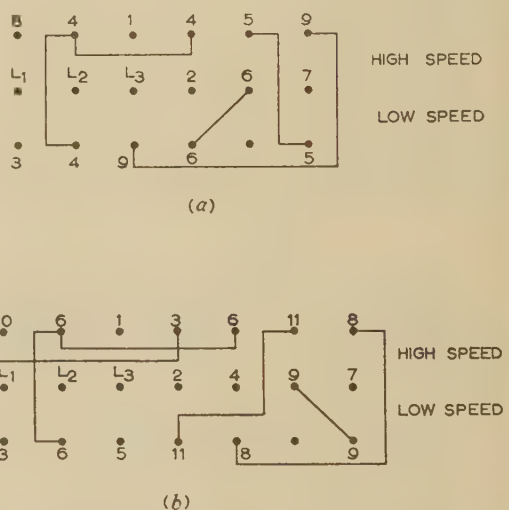


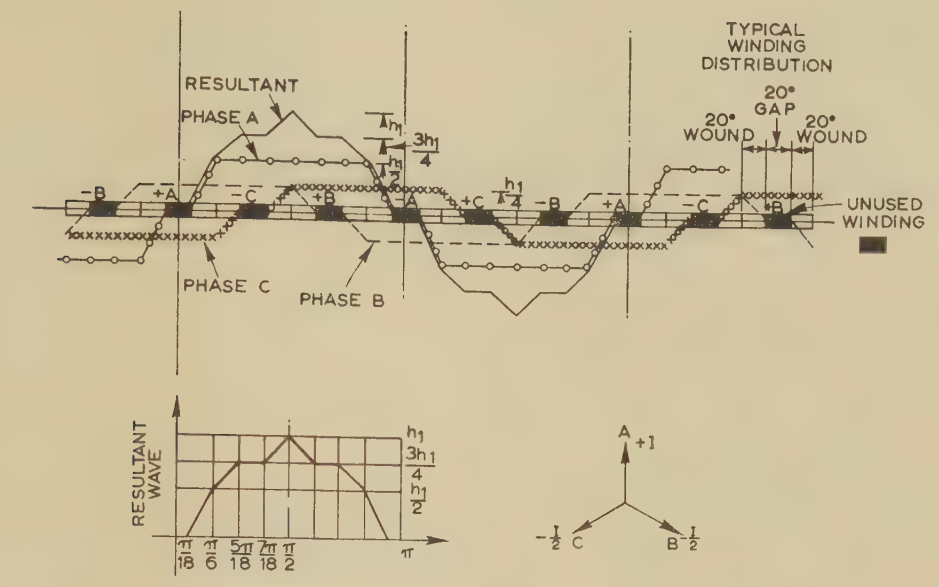
Fig. 6.—Switch controllers for 3 : 1 pole-changing.

(*a*) 6-gang double-throw controller for pole-changing 60°-spread winding. Numbers as in Fig. 5.

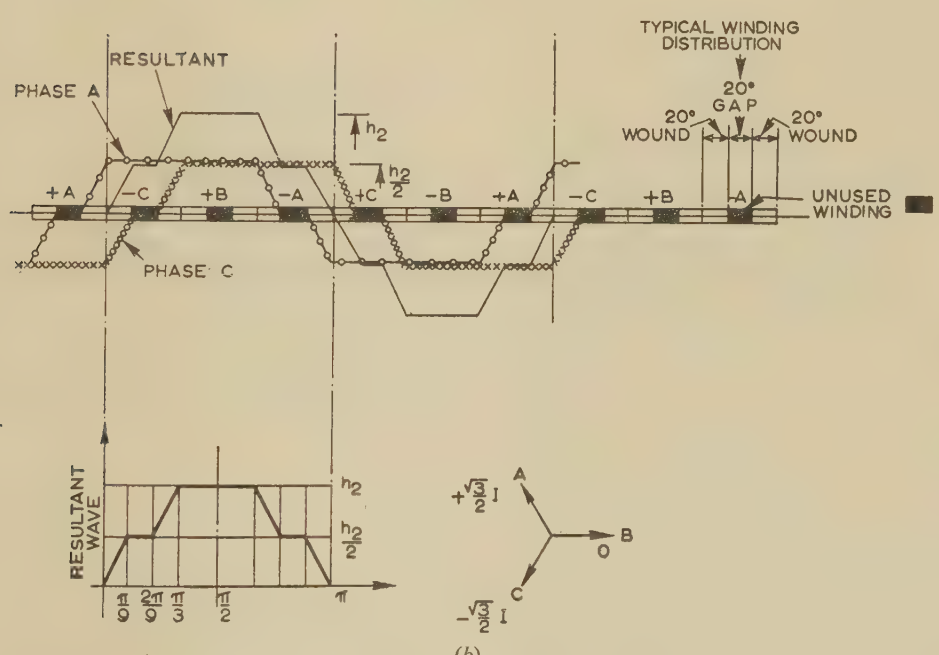
(*b*) 7-gang double-throw controller for pole-changing 120°-spread winding. Numbers as in Fig. 10.

(4.2) Elimination of Crawling Torques

In the examination of a proposed new winding for an inducti motor, it is always necessary to beware of possible crawli torques. Accordingly, two pairs of m.m.f. diagrams were co structed, each pair covering the two usual current-vector po tions. The first pair was drawn for a normal 3-phase windi having a 20° central gap in each phase band and the second p for a similar winding having a 20° gap at the edge of each pha band. The resultant waveforms are shown in Figs. 7(*a*) and 7(for the connection with a central gap, and in Figs. 8(*a*) and 8 for the connection with an end gap. As will be seen in Table



(*a*)



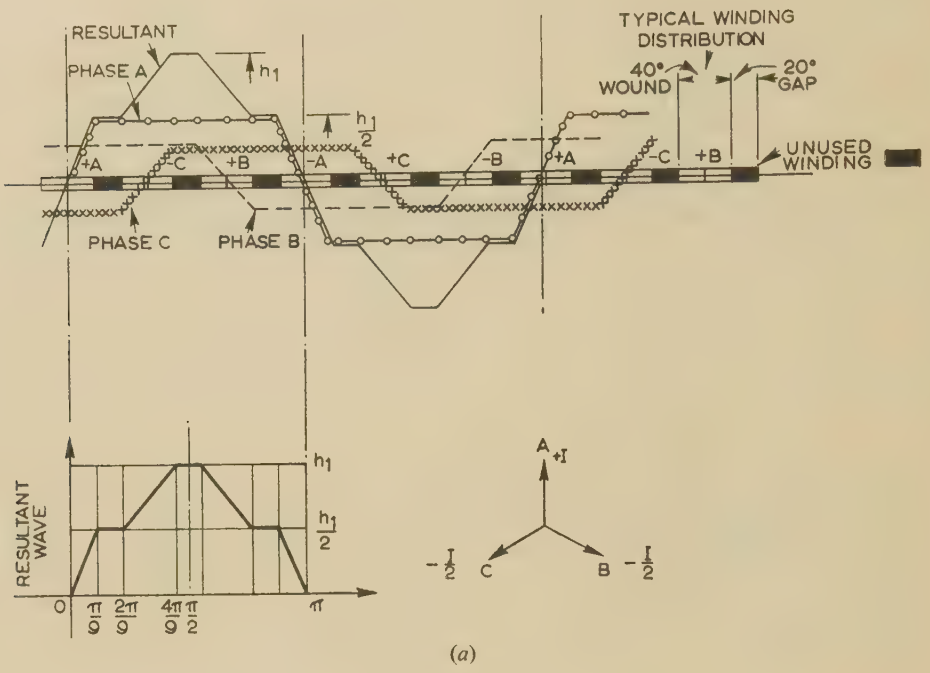
(*b*)

Fig. 7.—M.M.F. waveforms of 60°-spread, full-pitch, double-layer, 3-phase winding, 40° spread used, 20° central gap, for currents as shown by vectors.

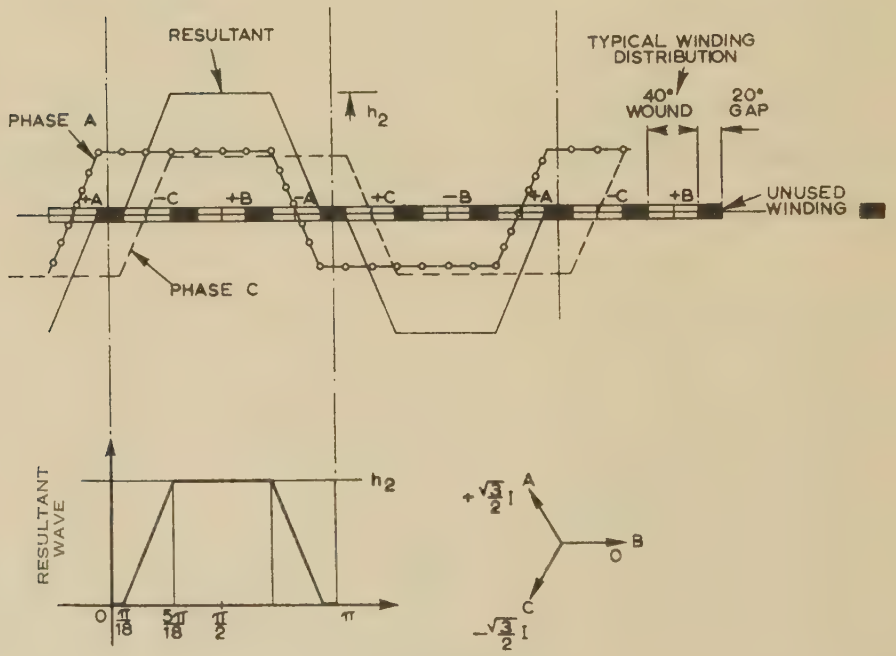
(*a*) Vector position I. $h_1 = \frac{3}{\pi}\sqrt{2}I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{72h_1}{\pi^2 m^2}\left(\cos^2\frac{m\pi}{6}\cos\frac{m\pi}{9}\sin\frac{m\pi}{18}\right)$

(*b*) Vector position II. $h_2 = \frac{\sqrt{2}}{\sqrt{3}}I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{72h_2}{\pi^2 m^2}\left(\cos\frac{m\pi}{6}\cos\frac{m\pi}{9}\sin\frac{m\pi}{18}\right)$

$h_2 = h_1 \cos\frac{\pi}{6}$.



(*a*)



(*b*)

Fig. 8.—M.M.F. waveforms of 60° spread, full-pitch, double-layer, 3-phase winding, 40° spread used, 20° gap, for currents as shown by vectors.

(*a*) Vector position I. $h_1 = \frac{3}{\pi}\sqrt{2}I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{36h_1}{\pi^2 m^2}\left(\cos^2\frac{m\pi}{6}\sin\frac{m\pi}{9}\right)$

(*b*) Vector position II. $h_2 = \frac{\sqrt{2}}{\sqrt{3}}I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{36h_2}{\pi^2 m^2}\left(\cos\frac{m\pi}{6}\sin\frac{m\pi}{9}\right)$

$h_2 = h_1 \cos\frac{\pi}{6}$.

Table 1

HARMONIC MAGNITUDES FOR 2/3 COMPLETE WINDINGS

Spread	M.M.F. harmonics	
	With centre third omitted	With outer third omitted
60°	−5th 3·3% + 7th 9·0%* −11th 3·7% +13th 0·4% See Fig. 7	− 5th 11·6%* +7th 3·8%* −11th 1·5% +13th 1·7% See Fig. 8
120°	−5th 14·1%* +7th 0·9% −11th 0·4% +13th 2·1%* See Fig. 11	−5th 2·1% +7th 3·1% −11th 1·3% +13th 0·3% See Fig. 9

The sign before each harmonic indicates the direction of rotation.
The asterisk (*) indicates those harmonics for which stable running could be obtained experimentally.

there was a serious 7th harmonic (9·0%) with the 20° central gap, but only a much smaller one (3·8%) with the 20° end gap.

Practice confirmed this theoretical analysis. Serious and incurable crawling occurred at any operating voltage with the 20° central gap, whereas steady crawling occurred only below about half voltage with a 20° end gap. Raising the voltage towards normal in the latter case brought the motor to full speed, though there was still some noise, and there would certainly be a dip in the speed/torque curve.

It was decided to abandon any idea of using a 20° central gap, and to circumvent the residual crawling tendency which occurs with the 20° end gap by casting a special aluminium rotor having a slot-skew equal to two 7th-harmonic pole pitches. This proved entirely successful in avoiding crawling torques at the higher speed, but the heavy skew greatly reduced the torque performance at the lower speed. The skew for the larger number of poles was necessarily equal to 6/7 of a pole pitch, giving a rotor chording factor of about 65%. Thus, although the machine with a specially skewed rotor gave something like ideal performance for the higher speed, the performance at the lower speed—which is likely to be more critical—was gravely worsened. Doubtless, use might be made of this arrangement, but it was decided to try another and better variant which has proved very satisfactory.

(5) FINAL MODIFICATION: USE OF PART OF WINDING AND 120° SPREAD

(5.1) 7th-Harmonic M.M.F. and Effect of Slot Permeance

The Fourier analyses given under Figs. 8(*a*) and 8(*b*) show that the amplitude of the 7th-harmonic m.m.f. for the winding with a 20° gap at the end of each 60° phase band is only about 3·8% of the fundamental, which is less than double the magnitude of the 7th-harmonic m.m.f. present in every standard full-pitch 3-phase winding. As is well known, the amplitudes of the harmonics in a standard winding diminish inversely as the squares of their orders. It seemed surprising that this order of increase should cause so considerable a tendency to crawl, and the possibility that the slot permeance distribution was imposing a flux harmonic of a much higher relative magnitude than the m.m.f. harmonic was therefore investigated. Since there were nine slots per pole, the normal crawling harmonics would be of the 17th and 19th orders ($m = 2s \pm 1$, where $s =$ the total number of slots per pole = 3, 6, 9, etc.), but the nine slots per pole were, in effect, divided into three slot-groups, each of three slots, by the slots containing the conductors which were switched out of circuit. It therefore seemed reasonable to suppose that the permeance harmonics might be, in this case, not slot harmonics but slot-group harmonics, which would naturally be of the 5th and 7th orders and would account for any harmonics of these orders being relatively more pronounced in the flux wave.

The matter is more fully discussed in Section 5.7, but it may here be mentioned that the conclusion stated there is that crawling takes place either when the m.m.f. harmonics are fairly large or when a moderate m.m.f. harmonic is exaggerated by permeance effects.

(5.2) Changed Slot Permeance

It was decided to investigate the effect of winding the machine with 120° phase spread, as in a true 3-phase winding, dividing this winding then into nine phase bands each of 40° phase spread. The new permeance distribution appeared likely to be much better, because one slot in three is filled with live conductors and the remaining two are half filled when 120° phase spread is used, as will be apparent from Figs. 9(*a*) and 9(*b*). There are, in this arrangement, no wholly disused slots. In principle, there seemed every reason to expect some reduction of 7th-harmonic effects by using 120° phase spread.

(5.3) Reduction of 7th-Harmonic M.M.F.

The m.m.f. waveforms for this new winding with 120° total phase spread, including a 40° end gap, are shown in Figs. 9(*a*) and 9(*b*) for the two typical vector positions, and the Fourier analysis shows that the 7th-harmonic m.m.f., although still the largest harmonic, is substantially reduced as compared with the value for 60° total phase spread, and is now about 3·1%. This in itself is a contribution to the reduction of 7th-harmonic torques, which will accentuate the effect of improved permeance distribution, but it is impossible to suppose that the striking practical improvement experienced was entirely due to the reduction of 7th-harmonic m.m.f. from 3·8% to 3·1%. It must also be due to more satisfactory permeance distribution.

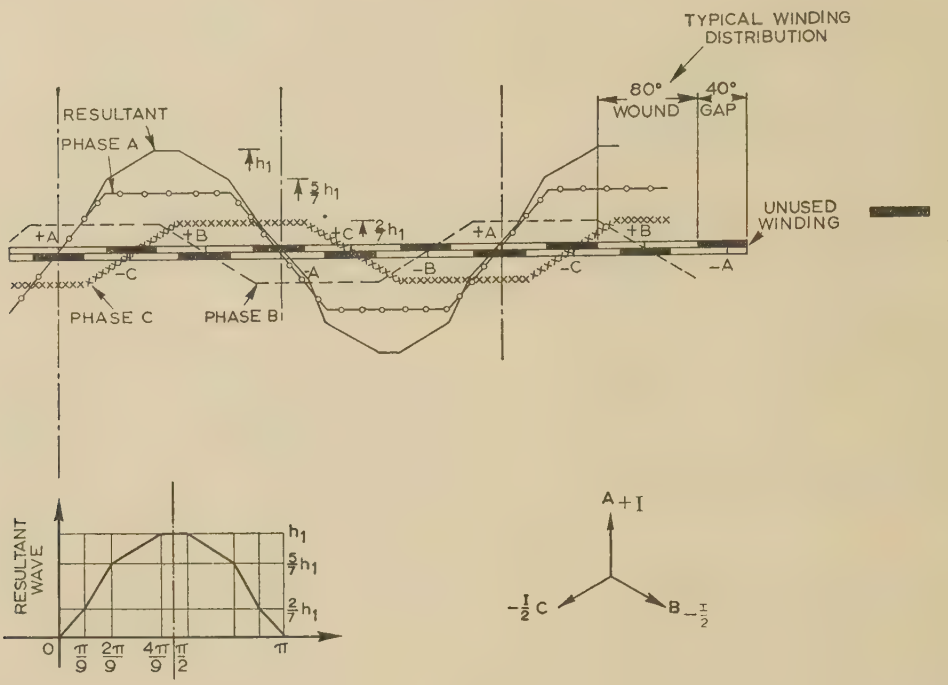
(5.4) Performance of Machine with 120°-Spread Winding

There was, in fact, no suspicion of crawling at any voltage or at any speed, using a perfectly normal rotor with the usual skew of one stator slot-pitch. The magnetizing current for a given voltage was of course slightly higher (about 15%) when the winding was reconnected for 120° phase spread. Some discussion of the magnetizing currents in this and related cases is contained in a companion theoretical paper.[1]

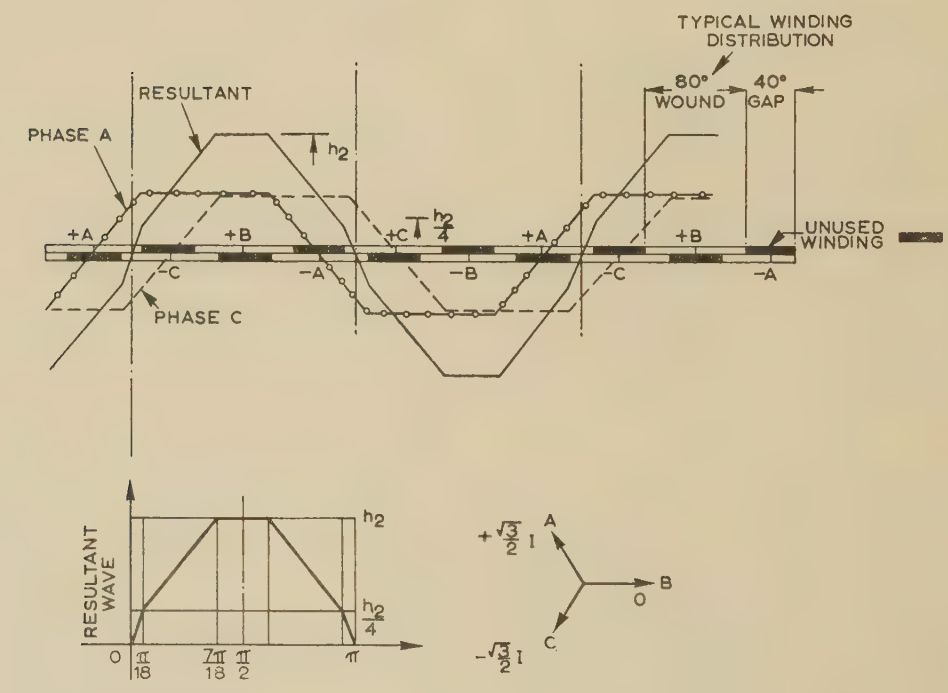
The short-circuit impedance for both numbers of poles was markedly less for 120° phase spread (roughly 25% less) compared with that of the same winding connected for 60° phase spread, and the torque rating would be correspondingly better. In addition, it is clear that the current distribution shown in Figs. 9(*a*) and 9(*b*) is very much better thermally than that of Figs. 8(*a*) and 8(*b*). With 60° spread, two-thirds of the slots are fully loaded and one-third carry no current; with 120° spread one-third are fully loaded and all the remainder are half loaded.

The winding as connected for the lower speed produces the normal m.m.f. waveforms associated with a 120°-spread 3-phase winding, which are well known to be identical in numerical harmonic content with those for a 60°-spread winding, though the peaked m.m.f. waveform corresponds to the current-vector position when one phase carries no current, and the flat-topped waveform to the vector position when the current in one phase has its peak value. This is the inverse of the relationship for the 60°-spread winding.

Full test figures for the machine with the 120°-spread winding



(*a*)



(*b*)

Fig. 9.—M.M.F. waveforms of 120° spread, full-pitch, double-layer, 3-phase winding, 80° spread used, 40° gap, for currents as shown by vectors.

(*a*) Vector position I. $h_1 = \frac{7}{6\sqrt{2}} I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{144 h_1}{7\pi^2 m^2}\left(\cos^2 \frac{m\pi}{6} \sin \frac{2m\pi}{9}\right)$

(*b*) Vector position II. $h_2 = \frac{\sqrt{2}}{\sqrt{3}} I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{18 h_2}{\pi^2 m^2}\left(\cos \frac{m\pi}{6} \sin \frac{2m\pi}{9}\right)$

$h_2 = \frac{8}{7} h_1 \cos \frac{\pi}{6}$.

are given in Section 6, but it may here be stated that the tests in general showed that a 3 : 1 pole-changing winding has been devised which is naturally free from crawling torques (and thus requires no excessive skewing to circumvent their effects) and which has a rating approaching 90% of the maximum frame rating for either speed.

(5.5) Connections of 120°-Spread Winding

The nine phase bands are connected as shown in Fig. 10, which is closely comparable with the method used for the

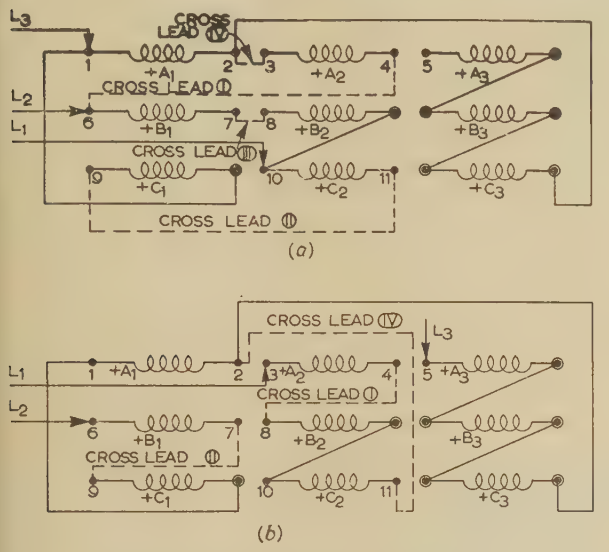


Fig. 10.—3 : 1 pole-changing winding, 120° spread, with connections modified to reduce number of leads to eleven.

(*a*) Connections for high-speed running. A_3, B_3 and C_3 carry no current.
(*b*) Connections for low-speed running.
Continuous lines indicate fixed connections; broken lines indicate switch connections.
In prototype, 18 leads were brought to terminals.
7 terminals shown thus ⊙ can be fixed connections.
11 terminals shown thus ● must be brought out to leads.

60°-spread winding (Fig. 5) except that the middle phase groups, when series-connected for the lower speed, do not now have to be reversed with respect to the outer phase groups, since the spacing between adjacent groups is 120° with respect to the larger number of poles, and not 60° as before. This involves an increase in the number of leads from 9 to 11, and an addition of one gang to the switch controller shown in Fig. 6(*b*). The numerical markings of Figs. 10 and 6(*b*) correspond.

It will be seen from Fig. 10 that, as before, one-third of the winding (an outer third of 40° spread) is omitted at the higher speed; this third is permanently connected for the lower speed, and can be wound with a coil pitch reduced from one pole pitch of the lesser number of poles to one pole pitch of the greater number.

(5.6) Omission of the Central 40° Section of Winding

The substantial reduction in 7th-harmonic content produced by 120° phase spread, as compared with 60°, was found to extend also to the 120°-spread winding with its central third omitted at the higher speed, although at voltages below half normal voltage the machine still crawled, but this time on the 13th harmonic, which is the next forward-rotating harmonic above the 7th. At higher voltages it pulled up to speed and ran normally, so that, overall, the crawling tendencies with 120° phase spread were less than with 60°, even with the middle third omitted.

These observed crawling effects were further studied by means of m.m.f. diagrams for this winding also, which are shown in Figs. 11(*a*) and 11(*b*). It will be observed from Table 1 that the predominating harmonics, by theory, are the 5th and the 13th; and it was found that, besides crawling on the 13th harmonic, this machine also exhibited in striking degree the reverse-crawling effect on the 5th harmonic, which is discussed in Section 9. The point is, however, only of theoretical interest, since the arrangement with the central gap, having a higher inherent harmonic content, would never be used for choice.

It is probable that the improvements effected throughout all these tests by raising the voltage are mainly due to saturation in the slot-group permeance variations, though it is true that the trough of the dip in the speed/torque curve will be raised by increasing the voltage, and this would tend to pull the machine above crawling speed if the load torque were low.

(5.7) Summary of Results with One-Third of the Winding Omitted

The various results obtained, both for 60°- and 120°-spread windings, may be summarized as in Table 1.

It will be observed that the harmonics, positive and negative, for which stable running was observed were either large m.m.f. harmonics (9%, 11·6% or 14·1%) or those harmonics of moderate size which were likely to be magnified by permeance effects. The main permeance harmonics for 60° spread are, as explained in Section 5.1, the 7th and 5th, but for 120° spread they are the 13th and 11th. This will be apparent when it is considered that in 60°-spread full-pitch windings the top and bottom of any one slot are in the same phase, whereas in 120°-spread full-pitch windings they are in different phases. This clearly doubles the effective number of slot groups and raises the orders of the permeance harmonics correspondingly.

(6) DETAILS OF TEST MACHINE AND TESTS

(6.1) Design Details

The motor as supplied was a standard industrial 4-pole, totally enclosed, fan-cooled machine, the stator slots being wound with exactly full-pitch double-layer coils, suitable for delta connection on a 700-volt 3-phase 50 c/s supply. There were 36 stator slots, and the individual stator coil ends were left unconnected by the makers, so that the 72 ends could be brought to a special terminal board for connection in accordance with the various circuits it was desired to test. The actual winding diagram of the machine finally used is shown in Fig. 12, which is also marked numerically to correspond with Figs. 10 and 6(*b*).

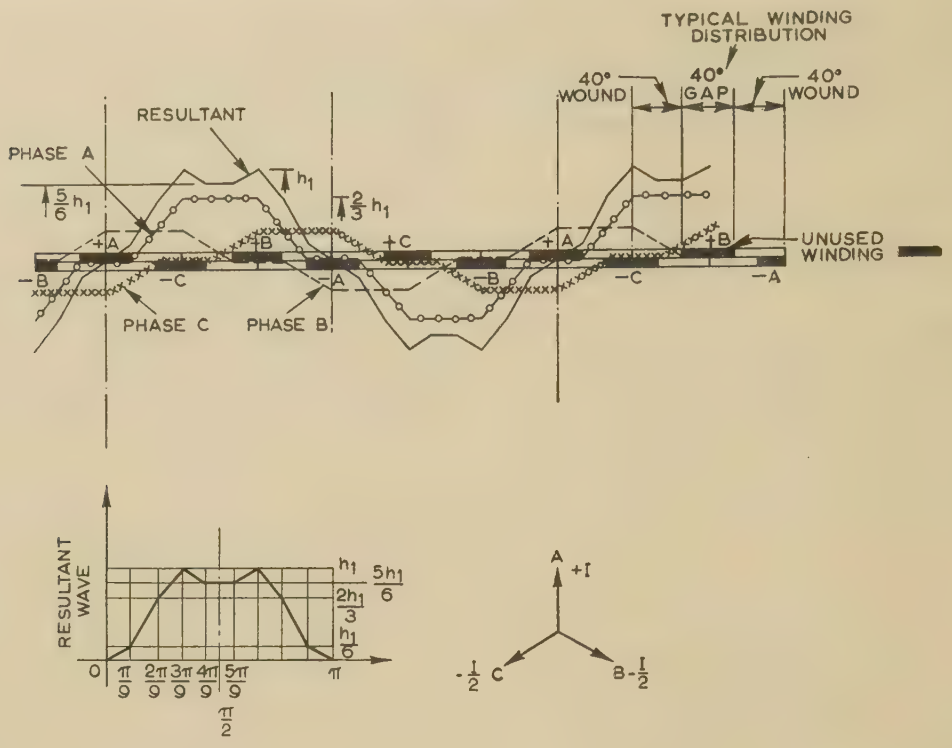
A machine wound for excess voltage was deliberately chosen, in order that, when part of the winding was omitted, the machine would be suitable for about 440 volts. A normal cast-aluminium rotor was used with 48 slots skewed about one stator slot pitch. The nominal rating of the machine was as follows:

700 volt; 3-phase; 50 c/s; delta connected;
5 h.p.; 1 450 r.p.m.; totally enclosed, fan-cooled; 50° C rise continuous.

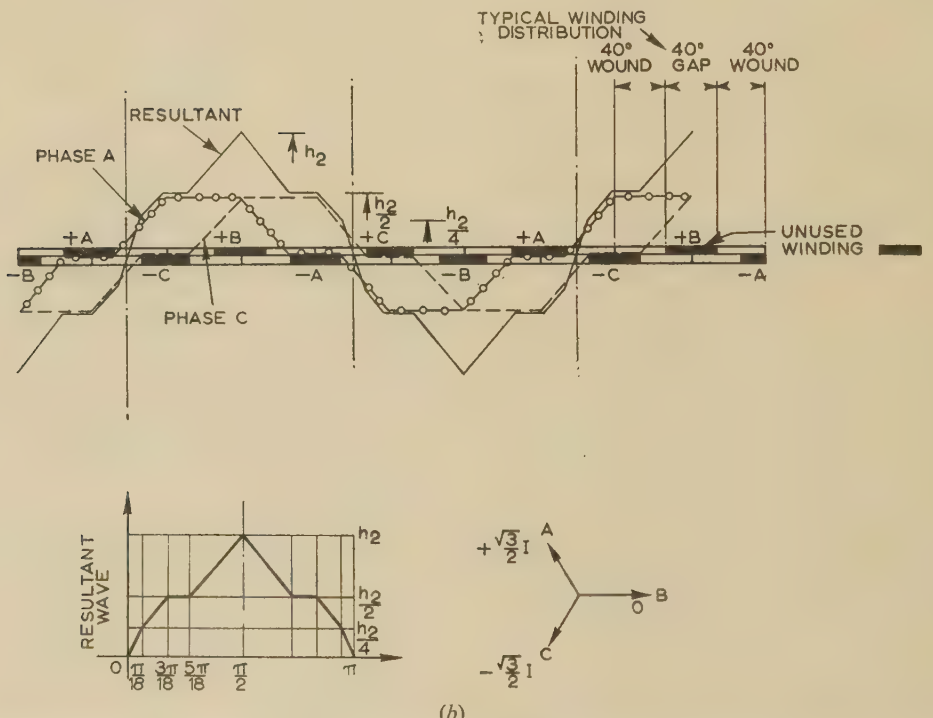
(6.2) Results of Heat-Run Tests

A series of heat runs on load, after reconnection in the way described in the paper, gave the following continuous ratings and performances:

(*a*) 440 volts; 3-phase; 50 c/s; 4-pole; delta-connected; 4·5 h.p.; 1 450 r.p.m.; power factor 0·87; efficiency 84%.
(*b*) 440 volts; 3-phase; 50 c/s; 12-pole; star-connected; 0·8 h.p.; 480 r.p.m.; power factor 0·62; efficiency 60%.



(*a*)



(*b*)

Fig. 11.—M.M.F. waveforms of 120° spread, full-pitch, double-layer, 3-phase winding, 80° spread used, 40° central gap, for currents as shown by vectors.

(*a*) Vector position I. $h_1 = \frac{1}{\sqrt{2}} I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{48 h_1}{\pi^2 m^2}\left(\sin\frac{m\pi}{9}\cos\frac{2m\pi}{9}\cos^2\frac{m\pi}{6}\right)$

(*b*) Vector position II. $h_2 = \frac{\sqrt{2}}{\sqrt{3}} I_a n$ ampere-turns/pole. Coefficient of mth harmonic is $a_m = \frac{36 h_2}{\pi^2 m^2}\left(\sin\frac{m\pi}{9}\cos\frac{2m\pi}{9}\cos\frac{m\pi}{6}\right)$

$h_2 = \frac{4}{3} h_1 \cos\frac{\pi}{6}$.

The fan fitted was of a small size, suited for the machine at 1 500 r.p.m., and the general proportions of the machine were more appropriate to this speed than to the usual 12-pole form.

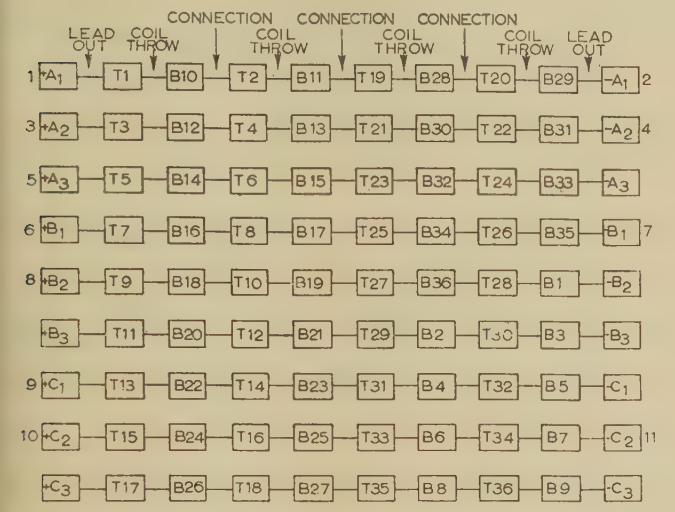


Fig. 12.—12 : 4 pole-changing winding, 120° phase spread. Winding diagram of final arrangement.

T: Slot-top.
B: Slot-bottom.

A larger fan and a higher ratio of diameter to length would almost certainly increase the relative rating at the lower speed. Further, as explained in Section 4.1, the copper loss at the lower speed could have been reduced considerably by winding one-third of the coils of pitch 1–4, instead of 1–10, but limited manufacturing facilities precluded alterations of this kind and the efficiency at the lower speed was consequently rather low relatively.

The standard machine ratings of a leading manufacturer give a ratio of rated power outputs for a given frame of this size for the same two speeds of about 5 : 1, and the pole-changing motor, even though not designed for this purpose, has approached very nearly to this accepted commercial performance. Further, the power factors obtained are almost identical with those in the rating lists of the same manufacturer, and the efficiency at the higher speed is also fully up to normal. The efficiency at the lower speed is rather less.

Whilst it is thus true that the continuous rating and efficiency at the lower speed are slightly less than might have been hoped for from a given frame, it is none the less true that in many possible applications speed reduction might also be required for intermittent use, in which case the point would be of no consequence. An entirely new arrangement is under development which may meet even this slight objection, besides serving other independent purposes.

(6.3) Torque from Short-Circuit Tests

The usual short-circuit tests were carried out, and the pull-out power was deduced in the normal manner. The results were as follows:

4-pole	Pull-out power	= 7·2 h.p.	Ratio: 1·6
	Full-load power	= 4·5 h.p.	
12-pole	Pull-out power	= 1·66 h.p.	Ratio: 2·1
	Full-load power	= 0·8 h.p.	

As previously explained, the ideal full-load power rating in the 12-pole condition is probably rather higher than the above figure, because the machine frame was not normally intended for this low speed.

It is worth remarking that the short-circuit reactance, both for 4-pole and 12-pole connections, was about 20% less with a 120°-spread winding, than with a 60°-spread winding, and the pull-out power was correspondingly increased. This was a welcome improvement, much greater than expected, which goes far to offset the increase in magnetizing current brought about by increased phase spread.

(7) EARLIER WORK ON 60°-SPREAD WINDINGS

After the modifications discussed in Section 4.1 had been tried, the authors' attention was directed to an arrangement already patented by Mayer.[5] The patent makes no allusion to the subject of crawling torques or to the necessity of skewing the rotor by an unusually large amount to eliminate them. Mayer's patent specification also proposed an arrangement for using only one-third (20° spread) of the winding at the higher speed; this connection has been tried experimentally, and the harmonic content calculated. Theory and experiment both revealed such high 7th-harmonic torques that the machine failed to reach full speed, and even when the specially skewed rotor was fitted the crawling still persisted, although the torque was weaker. The finite width of the bars, and the inexact construction, of the skewed cage left it still slightly responsive to 7th-harmonic fields, even though in theory it should be wholly insensitive to them.

(8) A POSSIBLE SLIP-RING MACHINE

All the tests were carried out with a squirrel-cage rotor, and it is expected that this form only is likely to find favour in practice, but it is worth noting that a 3 : 1 pole-changing arrangement can be wound very simply for a slip-ring rotor with three rings, if it is desired to introduce rotor resistance only for operation with the larger number of poles. For the smaller number of poles, the arrangement described below acts as an internally short-circuited winding, i.e. as a squirrel-cage winding.

The rotor can be wound 2-phase, with six phase bands connected into two groups of three in parallel, the three bands in each group having $2\pi/3$ spacing with respect to a 4-pole field and 2π spacing with respect to a 12-pole field. With respect to 4 poles each group is short-circuited on itself; with respect to 12 poles each group generates a terminal voltage, and the two groups have $\pi/2$ spacing and act as a 2-phase rotor.

In effect, the arrangement discussed in the paper can be adapted for 2-phase purposes, as described by Liwschitz-Garik[3]; but it would be equally possible to use the equivalent 3-phase rotor, though this would necessarily have 36 or 72 slots on both stator and rotor, and would therefore be undesirable if alternatives were available. It has, however, been thought appropriate to mention Liwschitz-Garik's paper,[4] since it seems to be the earliest publication foreshadowing the practical use of the principle. The primary windings used by Liwschitz-Garik were, however, standard independent windings of 3 : 1 pole ratio.

(9) AN EXAMPLE OF REVERSE-CRAWLING

The winding with 60° total spread, and a 20° gap at the edge of each phase band, can be seen from the Fourier analyses [Figs. 8(*a*) and 8(*b*)] to have a heavy 5th-harmonic field. As is well known, harmonics of the order $(6m - 1)$, where $m = 1, 2, 3$, etc., rotate in the opposite direction to that of the main field rotation, whereas harmonics of the order $(6m + 1)$ rotate in the same direction.

The existence and strength of the 5th-harmonic field in this

case was elegantly demonstrated by starting the machine (with a normal rotor) in one direction, switching off, and then switching on the supply in the reverse sequence, as the speed passed through one-fifth of synchronous speed. The machine continued to run steadily at this speed, in the reverse direction to that of the main field. If the main switch were then opened for a brief instant and reclosed, the machine ran through standstill and up to one-seventh of synchronous speed in the forward direction, thus showing the simultaneous existence of a backward 5th-harmonic crawling torque and a forward 7th-harmonic crawling torque. In order to obtain the initial start, the full winding was used, and the 20° phase band at the edge was cut out while the machine was running synchronously.

It is not suggested that this phenomenon is likely to have any application, but is of interest as an instructional demonstration.

(10) ACKNOWLEDGMENTS

The authors are indebted to Mr. G. Redfern, Chief Engineer and Director of Newman Industries, Bristol, for assistance in connection with the supply of a specially made machine and components, and to Mr. A. Walsh, Consulting Engineer, Metropolitan-Vickers Electrical Co. Ltd., for helpful advice.

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DISCUSSION ON THE ABOVE THREE PAPERS BEFORE THE UTILIZATION SECTION, 16TH FEBRUARY, 1956

Dr. W. J. Gibbs: One of the striking things about these papers is the evident fact that two separate groups of people working in two separate universities have applied their efforts to exactly the same problem without collaboration or even consultation. It suggests that there must be a clamorous demand for 3 : 1 pole-changing motors. However, the importance of these papers does not rest solely on whether the motors described in them meet an immediate need; it rests mainly on the degree to which they contribute to our knowledge and our understanding.

In their paper on theory and characteristics, Messrs. Barton, Butler and Sterling are not sufficiently precise in their statements. They do not make it clear that every constant-torque motor of their type must have a transformer, the necessity for which will not add to the popularity of the motor. Later on they say that, for constant-torque drives using a compromise magnetic circuit, a slight increase in frame size may be necessary. 'May' and 'slight' are woolly words, and in fact an increase in frame size cannot be avoided. Frame sizes increase in jumps which are by no means slight either in rating or in cost. In their second paper the authors are more precise and more realistic.

Prof. Rawcliffe and Mr. Jayawant are more modest in their claims, and say that the output of their motor approaches 90% of that of the corresponding single-speed motor, but the word 'approaches' is not precise. They avoid the transformer by omitting part of the winding in the high-speed connection, and this seems a better idea, especially since it simplifies the switching arrangements. The difficulty they had with crawling is not surprising; this is a troublesome phenomenon even in single-speed machines, and it is inevitably more troublesome in change-pole motors, where some of the known remedies such as slot skew have to be compromises between the optimum values for the two pole numbers.

Undoubtedly there is a demand in certain applications for a 3 : 1 change-speed motor, a demand met hitherto by a motor with two separate stator windings. Both sets of authors are quite right in claiming that their single-winding designs must produce a cheaper motor, but they should be warned that the reduction in cost can be completely wiped out if the switching arrangements are complicated. The two-winding motor has very simple switching arrangements, so much so that in the 2 : 1 range where both types are available the two-winding motor is occasionally preferred to the single-winding motor just for this reason. Unless the authors give this matter close attention they can lose the major advantage of their machines. When presenting the paper by himself and Mr. Jayawant, Prof. Rawcliffe described a yet newer type of motor with more than two speeds. For the 3 : 1 speeds he said that only six terminals are required. My opinion is that the reduction of terminals to six will make switching so much simpler that the motor will be preferable to the present one even though the rating falls by 10%.

Both sets of authors make an attempt to compare favourably their machines with single-speed motors. The true comparison is with the 2 : 1 change-speed motor, and the main field of application must overlap that of the 2 : 1 motor. It is unrealistic to try to equate the cost of a two-speed motor with that of a single-speed motor. Not only is there the increase in frame size, not made any the less by the introduction of the word 'slight', but even for the same frame size the cost will be higher. This is because they are special machines and in the design of such machines the slightest deviation from the norm is expensive.

Mr. W. Hill: As a designer of induction motors I have tried to replace machines which had two windings by change-pole machines, but I have been told that this would always be more expensive.

The penalty exacted for having two windings in one slot is only the increase of the stator copper loss. Apart from constant losses a large number of additional losses in induction motors are high-frequency losses—which can be as much as 4–10% of the total input to a machine; this fact explains that the two-winding machine requires only a very small increase in size.

Prof. Rawcliffe and Mr. Jayawant used an uninsulated cast-aluminium rotor with the number of rotor slots exceeding that of the stator slots by more than 30%. From the diagrams they produced, Mr. Butler and his colleagues appear to use a copper rotor, possibly with insulated bars and slots. Therefore, even as straightforward machines, the former is more likely to have a tendency to crawl than the latter.

The influence of insulation and the number of slots is clearly stated by Alger,* who says that the number of rotor slots must fall within certain limits. Both machines described exceed that limit by a large amount.

The addition of one or two oscillograms as records of speed/torque curves would have been preferable to plotting readings.

* ALGER, P. L.: 'The Nature of Polyphase Induction Machines' (1951, p. 174).

from d.c. machines. The latter introduces additional stray-load losses whereas an oscillogram record would show up the harmonic torques and would give reproducible measurements.

Industry will be greatly interested in the motor having only six leads, which Prof. Rawcliffe says is shortly to be produced. But unless the control-gear arrangements are simple, customers will not have any inducement to order this type of machine.

If there is no insulation on rotor bars the skew reactance is reduced considerably. Here again the difference between the two machines explains the fact that Prof. Rawcliffe does not mention skew reactance as a cast-aluminium rotor has no insulation on the rotor bars.

In industry, in trying to design machines, we are finding it very difficult to make up our own minds as to what really happens in induction motors. Prof. Rawcliffe and Mr. Jayawant, for instance, tell us in their paper that the torque is produced in the rotor bars. Even in industry we know that the torque is on the iron.

It is not that we cannot predict what is happening—that can be done very accurately—but we know that we are using analogies which in themselves may be obstacles to further advance. So far as I know, the way in which torque is produced in an induction motor has been glossed over in the literature of this and every other country. We should appreciate it if we could have something on that score in some future paper.

Prof. F. C. Williams: In a recent paper* Mr. Laithwaite and I described a machine which gave a continuously variable speed between limits, convenient limits turning out to be between 2 and 3 : 1. It is therefore obvious that we shall have an interest in a pole-changing scheme to extend this range. Our machine might be regarded as an interpolating mechanism between the fixed-speed and the pole-changing system.

In the design of our own machine we found considerable difficulty in getting enough copper into the stator. Therefore, to put two windings instead of one aggravates the difficulty. The authors have produced a scheme which enables the winding space to be used more efficiently and gives less stator resistance while still having the facility of the 3 : 1 change. We should be glad if the authors could tell us the effective stator resistance, using two separate windings and using this special winding arrangement.

Prof. Rawcliffe refers to the m.m.f. curves when certain of the stator parts are left disconnected. The so-called 'short stator' that we have grown familiar with in our machines consists of a stator winding of limited length used in conjunction with a rotor which is not of limited length. In such machines, the current in any given rotor bar does not fall to zero at the instant it leaves the stator, and therefore there is an m.m.f. operating at points outside the limits of the stator. In working out his m.m.f. curves I think Prof. Rawcliffe has assumed there was no m.m.f. over the unwound parts of the stator. Has he any thoughts on how rotor current might have influenced the m.m.f. in his machine when running?

Mr. P. Huggins: One point which is not entirely without importance is the extent to which a 3 : 1 pole-changing motor with a single stator winding can, with advantage, be used instead of the conventional 3 : 1 motor with its two separate stator windings. It may work out in much the same way as it has done with 2 : 1 pole-changing motors, where it is a matter of weighing the greater simplicity of wiring and control-gear needed with two separate windings against slight savings in total cost, motor size, motor weight and efficiency obtainable with a single stator winding. It would be interesting if the authors could give us some comparative costs in respect of their 3 : 1 motors.

Prof. Rawcliffe states that at top speed on his experimental motor the de-rating for pole changing is only from 5 b.h.p. to $4\frac{1}{2}$ b.h.p. Since I cannot see how it is possible to omit one-third of the stator winding without having to de-rate substantially more than 10%, I would inquire whether temperature runs were taken on the motor as a normal 5 b.h.p. single-speed motor and on $4\frac{1}{2}$ b.h.p. as a 3 : 1 pole-changing motor to prove that the temperature rise was, in fact, the same under both conditions.

The output powers quoted by Prof. Rawcliffe for the two speeds have the peculiar ratio of 5·6 : 1, which represents 1·85 : 1 in terms of torque. How does he propose to get appreciably away from this ratio where the drive demands something quite different—such, for example, as constant torque?

The authors' scheme for braking to standstill by what may be termed 'single-phase injection' is particularly interesting. As the authors explain, it necessitates a special rotor which can take one of three forms. Their description of one as 'a high-resistance rotor' tends to be misleading in that the resistance needs to be much higher than that associated with the general run of high-resistance rotors.

I must query a statement in the summary of the paper by Prof. Rawcliffe and Mr. Jayawant, namely that 'the machine is free from the crawling torques common to pole-changing motors'. By suitable slot numbers and suitably distributing the stator winding, 2 : 1 pole-changing motors are made to exhibit a ratio of minimum running-up torque to static torque which is up to the same standard as single-speed motors. Much experience of this was gained during the years 1929–33 in the production of 2 : 1 pole-changing 25/50 c/s dual-frequency motors in anticipation of frequency standardization.

Prof. J. E. Parton: The coincidence of the same idea having been pursued independently in two centres unbeknown to each other has been referred to by other speakers. Apart from the remarkable nature of this coincidence the thing which interests me most is the underlying theory of pole-changing. Casting one's thoughts back over the many papers on pole-changing produced in the last fifty years, there is the 2 : 1 consequent-pole system, the coil regrouping method, Hunt's special superposed windings, the Creedy phase-change method and now this 3 : 1 system.

Such apparently diverse ways of effecting pole-change would lead one to suspect that there is a common underlying theory embracing all. One such theory appears to be that of ringing all the possible sequence changes of a polyphase system of a high order. Starting with a 3-phase system the possible connections are those for positive (sequence-1), negative (sequence-2) and zero sequence (sequence-0, or -3). These give magnetic fields moving at $+1$, -1, and 0 times synchronous speed respectively.

Table A gives the speed of the greatest component of m.m.f. for windings fully pitched, for the various sequence connections of a few of the odd-integer lower-order polyphase systems. From this Table it can be seen that the 3rd or 6th order of a 9-phase system gives m.m.f. of speed $+\frac{1}{3}$ or $-\frac{1}{3}$ of synchronous speed. Now the 3rd- or 6th-sequence order of a 9-phase system is the positive- or negative-sequence 3-phase system. Hence 3-phase voltages applied to a 9-phase winding in 3rd- or 6th-sequence order will give m.m.f.'s of $+\frac{1}{3}$ or $-\frac{1}{3}$ of synchronous speed. This is the basis of the two machines described in the papers. I should very greatly like to try out one or other of these two machines with a 9-phase supply. It seems probable that four different speeds could be obtained.

Systems of even phase number can be introduced into Table A; and also m.m.f.'s with even fractions ($\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{6}$, etc.) of synchronous speed can be produced only if the windings are not fully pitched for the smaller pole number. In the 1 : 2 pole-change system

* Williams, F. C., and Laithwaite, E. R.: 'A Brushless Variable-Speed Induction Motor', *Proceedings I.E.E.*, Paper No. 1737 U, November, 1954 (102 A, p. 203).

Table A

SPEED OF THE GREATEST COMPONENTS OF M.M.F. GIVEN AS A FRACTION OF THE SYNCHRONOUS SPEED FOR THE LEAST NUMBER OF POLES

Sequence order	Number of phases			
	3	5	7	9
0	0	0	0	0
1	-1	-1	+1	+1
2	1		$-\frac{1}{2}$	$-\frac{1}{3}$
3			$+\frac{1}{3}$	$+\frac{1}{5}$
4		-1	$-\frac{1}{4}$	$-\frac{1}{7}$
5			$+\frac{1}{5}$	$+\frac{1}{9}$
6			-1	$-\frac{1}{9}$
7				$+\frac{1}{7}$
8				-1

the pitches would be, say, of 120° to 240° or, as is more common, 90° to 180°. This is necessary in order to introduce the even harmonics in the m.m.f. waveforms. It is possible that the 6 : 3 : 2 : 1 pole-change machine which Prof. Rawcliffe is developing could be the 3 : 1 system with under-pitched coils to give the even harmonics for halving both speeds by the consequent-pole method.

At present there is some possibility that all the known pole-change schemes will fit into a general theory such as I have described, and I shall look forward with great interest to seeing Prof. Rawcliffe's new motor, particularly if it falls outside this general theory.

Mr. G. Redfern: I feel that the comparison of these 3 : 1 pole-changing motors with single-speed motors is misleading. I feel with one of the previous speakers that the conclusion that no loss of output is suffered may be due to the fact that the authors have not been so conservative in their ratings as the manufacturers.

With regard to a comparison with the conventional 3 : 1 two-winding machine, it would be accepted, I think, that the maximum increase in frame size from the machine described would be one frame size larger in diameter. I base that on the reasoning that the rotor diameter and the core length would be the same as for the two-winding machine, and the larger outer diameter would provide ample winding space for the extra copper. This would be a better starting-point for economic comparison, which must take into account the much more expensive control-gear.

This method of economic comparison would be far better than looking at manufacturers' lists, because of the confusion that arises on account of their conservative rating and the possibly less conservative rating of the authors.

Dr. Barton and his colleagues discount the effect of larger overhang on the low-speed winding because of the increased cooling areas. This cannot be discounted on totally enclosed fan-cooled motors, which are very popular for machine-tool drives.

The use of change-pole induction motors for reducing reversal losses is new to me. I would agree that it possibly has great applications, but I do not think these need be restricted to the particular 3 : 1 pole-changing arrangement suggested, especially since the larger rotor diameter which is mentioned in the paper is in my opinion not necessary on the arguments I have previously put forward.

One other point which struck me was the demonstration of the value of Alger's overhang leakage reactance formula, and I thought the application well demonstrated. Anyone would, I am sure, have been very hesitant to apply any empirical formula to the end-winding calculations on the third-speed winding. Indeed, I doubt whether even Alger thought of such a peculiar case as this. I was not satisfied until I had checked through the derivation. I wonder whether Mr. Butler and his colleagues had the same doubts.

Mr. E. W. Krebs: Since all the papers seem to start from the premise that no 3 : 1 pole-change single winding with a reasonable number of terminals existed previously, I should like to draw the authors' attention to a two-speed winding which developed some 20 years ago.* This winding, which has 120° spread and generally requires 12 terminals (see Fig. A), is suitable for any pole ratio, although it is most useful for small ratios of 3 : 2, 4 : 3, etc. The harmonic content of the field

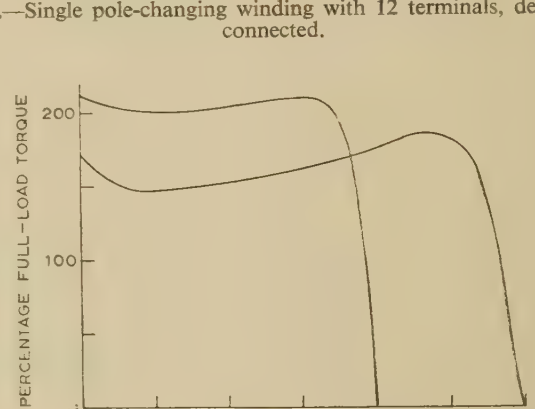


Fig. A.—Single pole-changing winding with 12 terminals, delta-delta connected.

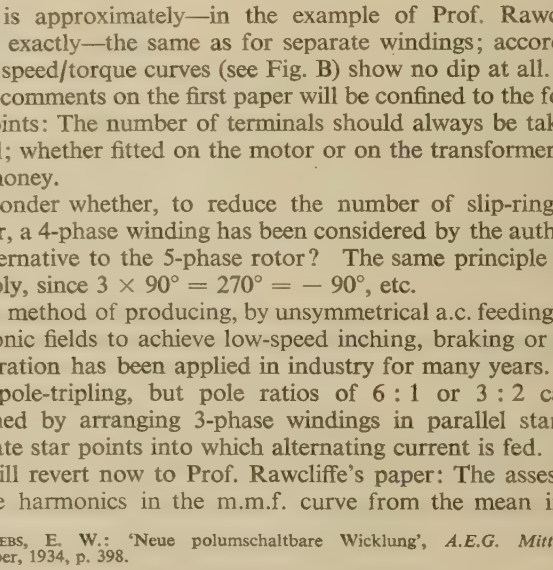


Fig. B.—Tested speed/torque curve of double-cage motor; winding as above.

curve is approximately—in the example of Prof. Rawcliffe's paper, exactly—the same as for separate windings; according to tested speed/torque curves (see Fig. B) show no dip at all.

My comments on the first paper will be confined to the following points: The number of terminals should always be taken as a total; whether fitted on the motor or on the transformer, they cost money.

I wonder whether, to reduce the number of slip-rings still further, a 4-phase winding has been considered by the authors as an alternative to the 5-phase rotor? The same principle seems to apply, since $3 \times 90° = 270° = -90°$, etc.

The method of producing, by unsymmetrical a.c. feeding, large harmonic fields to achieve low-speed inching, braking or gentle acceleration has been applied in industry for many years. Not only pole-tripling, but pole ratios of 6 : 1 or 3 : 2 can be obtained by arranging 3-phase windings in parallel star with separate star points into which alternating current is fed.

I will revert now to Prof. Rawcliffe's paper: The assessment of the harmonics in the m.m.f. curve from the mean instead

* KREBS, E. W.: 'Neue polumschaltbare Wicklung', *A.E.G. Mitteilungen*, December, 1934, p. 398.

of the stepped curve is open to criticism, since in a squirrel-cage motor the skew is rarely 100% effective. If the stepped wave is used, the amplitudes of the 7th harmonic are 6·85% and 4·03% for 60° and 120° spread, which may explain the apparent inconsistency in crawling.

The comparison for the two spreads would yield different results if each case were based on the optimum coil pitch, which is 1 to 9 for 60° spread. Since fewer terminals are needed for the latter, it may well be the better arrangement.

Mr. J. C. M. Sanders (*communicated*): It behoves industry first of all to support the efforts of the authors in exploring the avenues opened up by the developments described. Not only are there possibilities of commercial exploitation of the various inventions, but—perhaps more important—there is the likelihood that industrial engineers would be stimulated by discussions with men who have time to think. Secondly, it is necessary that industry should clearly define the problems which it has to face, not with a view to directing the research programmes of universities and colleges, but simply to indicate where existing knowledge is insufficient.

On the other hand, in evaluating the results obtained, industry requires the utmost possible information on the equipment used, and it would be interesting to know what limitations of size of machines the authors envisage.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSION

Dr. T. H. Barton, Messrs. O. I. Butler and **H. Sterling** (*in reply*): Points raised more than once in the discussion will be dealt with first.

The relative costs of a 15/5 h.p. 4/12-pole screen-protected motor and control equipment are given in Table B for the dual- and single-winding arrangements; the latter employs a simple form of 3/2 phase conversion and two change-over contactors, and is still somewhat the cheaper. In general, the cost ratio of the dual- and single-wound motors alone is about 3 : 2; the substantial saving in the latter case arising from reduced material and labour costs. In particular, replying to Dr. Gibbs, it depends largely on the manufacturer's organization whether the slightest deviation from the normal design is expensive.

Table B

COMPARISON OF DUAL- AND SINGLE-WINDING MOTOR COSTS

Type	Dual winding	Single winding
	%	%
Motor cost	67	44
Starter	33	39
Transformer	—	7
Total	100	90

First cost, however, is not the only criterion of merit. Efficiency, freedom from harmonic torques, weight and size are important factors. In these respects, our machine approaches more closely to, and in some cases attains, the ideal set by the single-speed motor. Nevertheless, the improved flexibility and simpler control gear of the dual-wound machine will still make it preferable for some applications.

Mr. Huggins and Mr. Redfearn suggest that the 3 : 1 dual-wound motor be used as a basis of comparison, while Dr. Gibbs advocates the 2 : 1 single-winding motor. We used the single-speed motor since it provides the optimum performance for a given frame size and therefore is the logical basis for assessing the merits of any pole-changing design. In addition, however, we included a detailed comparison with the 2 : 1 motor.

The simultaneous interest in different forms of 3 : 1 motor at two separate universities is not surprising: it is a logical development of the recent papers by Brown and Butler, cited in the present papers.

Contrary to Dr. Gibbs's statement, every constant-torque 3 : 1 motor discussed by us does not require a transformer; when such is required, it is clearly indicated. We would point out that a 3/2 phase transformer was used to reduce the number of terminals, thereby simplifying the switching arrangement, and providing a full utilization of the windings at both speeds.

Dr. Gibbs's criticism of lack of precision in the first paper is hardly justified, since we quote definite outputs in Section 7 and plainly state that no increase on the frame size of a standard 3 h.p. 12-pole motor is necessary to provide a 3/9 h.p. 12/4-pole machine. In most cases, where the sizes of the equivalent single-speed motors differ appreciably, the larger frame will be adequate for our pole-changing machine.

We assure Mr. Hill that his informant on the costs of 2 : 1 single- and dual-wound motors has been too sweeping, and even more so for the case of the 3 : 1 motor detailed in Table B. The rotor bars of our motors were uninsulated and a hard driving fit in the slots. The absence of crawling torques is not surprising, since the m.m.f. distributions are precisely those of the equivalent single-speed motors. The stray loss of the calibrated d.c. machine was relatively small, and the accuracy of the torque/speed measurements exceeds that of any published oscillograph method.

Replying to Prof. Williams, if identical slots and effective turns per phase are used, the resistance of the dual-wound machine will be more than double that of the single-wound machine at the high speed and somewhat less than double at the low speed.

Mr. Huggins is correct in pointing out that the rotor resistance for asymmetric braking is much higher than is normally used. It is for this reason that the various unconventional rotor windings have been described.

Prof. Parton's comments are most interesting and we look forward to a more detailed account of his theory.

We assure Mr. Redfearn that the figures for ratings are based upon the appropriate design data and not upon rating figures for the frame size. Our comments regarding end-winding heating apply, of course, to the protected type of motor. Irrespective of the possibility of using the same rotor diameter for any type of pole-changing arrangement, we would point out that the reduction of reversal losses can be obtained in our machine with no increase in motor size and no sacrifice in performance by designing the machine solely on the basis of the high-speed performance.

In reply to Mr. Krebs, a 4-phase rotor winding is unsuitable because of the poor winding utilization associated with a spread of 270° at the higher pole number. The corresponding spread for a 5-phase rotor is 108°.

In reply to Mr. Sanders, so far as can be seen there is no limit, either up or down, to the size in which our machine can be built.

Prof. G. H. Rawcliffe and **Mr. B. V. Jayawant** (*in reply*): One cannot be precise in claims about ratings from tests on only one machine, but we think that our rating is at least 80% of the full frame rating at both speeds; it may be more. Since writing the paper we have found new methods of reducing the numbers of leads from 11 to 9 or 6; to the former without reduction in rating and to the latter with some loss of rating,

but with an extremely simple controller. We are thus able to produce a 3 : 1 two-speed winding, with only a very slight increase in complexity of the controller; and we note with interest Dr. Gibbs's opinion that our last variant is likely to be commercially most acceptable.

In reply to Mr. Hill, we used for our tests a standard industrial machine supplied with 36 unwound stator slots and 48 rotor slots. The choice of rotor slot number was not ours, but the machine operated satisfactorily. It may be that other rotor-slot numbers would be better, but we have eliminated crawling even with this number. We are, of course, aware that the torque is actually exerted on the iron, because of the current in the conductors, and is not actually exerted on the conductors themselves. None the less, the torque is exactly what it would be if it were exerted on the conductors in the absence of iron. The point is dealt with in many treatises on electromagnetism, such as that by Moullin.

In reply to Prof. Williams, we have not assumed that there is no m.m.f. on the unwound part of the stator. There is, of course, always an m.m.f. at every point between two sets of parallel conductors carrying current in opposite directions, whether or not there are blank slots between them.

We tested our machine as a standard machine before doing our own tests. The reduction in rating is only moderate because the remaining conductors can be more heavily loaded when some are out of circuit. We ought not to have said that 'crawling torques are common in pole-changing motors': we meant that they are liable to occur unless the designer is sufficiently skilled to avoid them.

Mr. Krebs's contribution is of great interest and we shall study it with care. We performed the stepped m.m.f. waveform analysis after writing the paper, and we agree that the results tend to support our experimental tests. We also have in hand an experimental examination of the 60° spread winding, and shall offer the conclusions as a short supplementary paper.

In reply to Mr. Sanders, our designs were perfectly standard apart from the special features described in the paper. We strongly suspect that, since a satisfactory and simple 3 : 1 pole-changing winding has been produced, it will find industrial application; but even if this were not so, we should still say that we have produced a new piece of engineering apparatus which has the great merit that it works satisfactorily, and that we have greatly enjoyed its production.

DISCUSSION ON

'THE APPLICATION OF SYMMETRICAL COMPONENTS TO THE MEASUREMENT OF PHASE DIFFERENCE IN SINGLE-PHASE CIRCUITS'*

WESTERN CENTRE, AT BRISTOL, 12TH MARCH, 1956

Mr. B. M. Bird: Would it not be possible to employ a combination of Allcutt circuits to give, say, the positive-sequence component of an unbalanced voltage system and hence obtain a perfectly balanced system from one in any state of unbalance?

Mr. G. O. McLean: While I appreciate the author's ingenuity in making the miniature rotation indicator from two pigmy lamps, I would assure him that we in the supply industry would like all our instruments of such dimensions. Will he give comparative costs of this type of rotation indicator and the more normal induction type?

Mr. A. G. Milne: The theory of symmetrical components has proved to be a valuable mathematical tool for the solution of transmission and protection problems. Could it be made equally valuable for application to the production of cheap and reliable instruments for protection purposes? I realize that there have been in existence for some time negative-phase-sequence relays, but these are expensive and have not always proved completely satisfactory.

The author shows how neatly the unbalance condition can be broken down into two balanced sequences of opposite sign, and by the simple expedient of shifting vectors he shows how a simple rotation device for single-phase circuits can be provided. Could a similar process be applied for protective devices starting with two phases of the balanced positive sequence system in healthy conditions leading to a resultant unbalanced state under fault conditions?

Mr. F. P. Phillips: In what respect is the phase sequence indicator described superior to the well-known Varley circuit using two lamps and a capacitor or inductor?

Mr. R. L. Russell (*in reply*): If the attention devoted to a topic is any evidence of its importance, the lack of balance between phases of a polyphase system no longer presents the problem it once did. For testing purposes in the laboratory, however, it is frequently desirable to have an exactly balanced supply, and for work on symmetrical component measurements it is essential. Proposals for constructing a static balancer as an assembly of sequence selective networks to form a standard piece of laboratory equipment are precisely those suggested by Mr. Bird.

A precise answer to Mr. McLean's question will be available when the device has been manufactured. An estimate, based on a prototype model, is that the cost of the new indicator should be about half that of the orthodox induction type.

In the new indicator, one lamp is bright and the other is dark and the response is virtually independent of the lamp characteristics. The performance of one lamp is quite independent of the other.

In the Varley circuit referred to by Mr. Phillips, it is the mutual behaviour of the two lamps and capacitor (or choke) on which the indication depends, and, for example, should one lamp fail the other will be bright whatever the phase sequence. Furthermore, the Varley method requires the operator to make an assessment of the relative brightness of two lamps between which there may well be little to choose, especially if the lamp characteristics are dissimilar. The new indicator is a 'fail-safe' device which yields a more positive and reliable result than does the Varley method.

The simple reply to Mr. Milne's question, if the answer is restricted to principles and performance specifications are ignored, is that protection devices based on the measurement of phase differences can be envisaged. When, for example, two of the phase quantities of a 3-phase system are supplied to the bridge and ratiometer, which together form a phase-angle meter, a steady reading of (120/2)° will be obtained under balanced conditions. Under fault conditions this setting would be disturbed. The response could be mechanical, in terms of shaft rotation, or electrical if a search coil were used in place of the meter movement. There are a number of ways in which the principles discussed can be applied to control and measurement problems.

* RUSSELL, R. L.: Paper No. 1758, February, 1955 (*see* 102 A, p. 80).

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Abstract No. 2114
June 1956

POWER STATION AUXILIARY PLANT

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(ABSTRACT *of a paper which was received by* THE INSTITUTION OF MECHANICAL ENGINEERS *10th June*, 1955, *and was read at a joint meeting of* THE INSTITUTION OF MECHANICAL ENGINEERS *and* THE INSTITUTION OF ELECTRICAL ENGINEERS *6th January*, 1956.)

Some of those aspects of power station auxiliary services are discussed on which decisions have to be taken at the planning stage and which apply particularly to stations equipped with generating sets upwards of 60 MW working at steam conditions upwards of 900 lb/in^2 and 900° F. Depending on steam pressure and certain other design features, the maximum simultaneous demand taken by unit auxiliary services is likely to be between 5·5 and 6·5% of station output, and the further maximum demand taken by non-unit services between 0·4 and 0·7%. In a typical station, unit transformers, which are connected to generator terminals, should be of the 5 000 kVA size for 60 MW sets and of the 10 000 kVA size for 120 MW sets. The station transformers, which supply non-unit services as well as unit services on certain occasions, should be 5 000 kVA or 7 500 kVA in a station with six 60 MW generating sets and 12 500 or 15 000 kVA in a station with six 120 MW sets.

The justification for expenditure to increase availability, such as that on auxiliary plant items, depends on a quantitative assessment of the financial consequences of a forced outage. Hence decisions about duplication of plant items should be based on actuarial methods and on records of all failures in the past, including those that do not result in loss of generating capacity. When financial loss occasioned to the public by curtailment of supplies is taken into the calculations, it is found that the margin of spare plant connected to the British Grid system is probably very close to the most economical figure.

The high cost of feed heaters designed to withstand full boiler pressure makes the split-feed-pump scheme economical. With this there are two pumps in series, feed heaters being between them. It is found on an actuarial basis that it is more economical to provide standby feed-pump capacity by installing two full-duty than three half-duty pumps. With constant-speed pumps excess head has to be destroyed in a feed-water regulator, with resultant loss of thermal efficiency and excessive wear of valve seatings. Hence the cost of variable-speed drive of feed pumps has a strong economic justification.

The total capitalized cost of boiler-fan consumption per kilowatt is estimated for induced-draught fans at £170 at a load factor of 50%, and at £230 at a load factor of 80%. The corresponding figures for forced-draught fans are, respectively, £140 and £180. They are lower because most of the power input reappears as heat in the furnace and is reconverted to electrical energy at station efficiency. A cost comparison of various means of controlling the draught shows that damper control is very wasteful, even at maximum continuous rating of the boiler, and more so at reduced ratings. For, it is inevitable in practice for the fan motors to be provided with an excess of power over actual requirements if an adequate margin is to be allowed for uncertainty about the actual resistance to draught presented by the boiler, as well as for working at reduced frequency and with fouling of boiler tubes. Inlet vane control is more economical and can sometimes be justified. For other installations the high cost of variable-speed drive is more than compensated by the reduction in fan consumption that accompanies it.

There are occasions when more steam has to be generated in the boilers than can be used by the turbines. The necessity may arise, first, during pressure raising, when the temperature of the superheater has to be kept to a safe value by passing steam through it; secondly, when the load on the turbine is below the boiler load at which the burners keep alight; and thirdly, when a turbine is put back into service after a shut-down that has lasted for sufficient time for an appreciable difference of temperature to occur between the steam range and the turbine. If the surplus steam is blown off to atmosphere, the noise constitutes a nuisance to residents in the neighbourhood of the station and conditioned water is wasted as well as heat. It is hardly practicable to save the heat, but the water can be saved by a method known as steam dumping. One suggested method is to pass the surplus steam through diffusers incorporated in the reserve feed tank. To dissipate the heat thus passing into the water, this would be circulated through the main condenser by means of the extraction pump. Another inexpensive provision for steam dumping would be a flash vessel into which the steam was passed and in which it was condensed by a spray of water; it would drain to the main condenser. The kinetic energy in the steam would be dissipated by collision between molecules if the steam were admitted from opposite sides of the vessel.

It is important to provide such an amount of circulating water that the most economical temperature difference is maintained between inlet and outlet of the condensers. Typical economic differences are from 12° F to 17° F for river and estuary stations, and from 17° F to 21° F for cooling-tower stations. The latter are worked most economically when a bus main enables all the cooling towers to be kept in service even when some generating sets are shut down, for the cooling towers reduce the circulating water temperature to a lower value when lightly than when heavily loaded. It pays to adjust the quantity of circulating water with changes both of load and of weather. When a bus main is provided, a sufficiently fine adjustment is obtained by varying the number of pumps in service and the high cost of variable-speed circulating pumps cannot be justified. When there is a bus main, a spare pump can be justified only for a station equipped with a very small number of generating sets.

The authors are with Kennedy and Donkin.

The full text of the paper with discussion will be published in the *Proceedings of The Institution of Mechanical Engineers*, 1956, 170.

DISCUSSION ON
'ALUMINIUM-SHEATHED CABLES'*

Before the North-Eastern Centre *at* Newcastle upon Tyne 25*th October*, *the* Mersey and North Wales Centre *at* Liverpool 1*st November*, *the* North-Western Centre *at* Manchester 2*nd November*, *and the* North-Staffordshire Sub-Centre *at* Stone 13*th December*, 1954, *and the* Southern Centre *at* Portsmouth 5*th January*, *the* Western Centre *at* Bristol 7*th February*, *the* South Midland Supply and Utilization Group *at* Birmingham 14*th February*, *and the* South-Western Sub-Centre *at* Plymouth 24*th March*, 1955.

Mr. A. C. Bryant (*at Newcastle upon Tyne*): When the new oil refinery at Grangemouth was being constructed, aluminium-sheathed cables were provided for giving electric supplies to mobile cranes, etc. The cables were laid in a shallow trench about 6 in deep and then the level of the whole area was raised by 2 ft by the dumping of the inert and hard residue remaining after the oil has been extracted from shale. During the raising of the general level of the ground, lorries, scrapers and rollers were continually crossing over the cables laid in the shallow trench. After several years, when the construction of the refinery had been completed, the cables were lifted and as they were found to have suffered no mechanical damage they have now been re-employed elsewhere.

In a market in Aberdeen, which was quite an old building with numerous brick pillars, we erected a 0·15 in^2 4-core paper-insulated aluminium-sheathed cable. In this case the fixing centres of the supports were approximately 12 ft apart and the cable even with this spacing was found to have negligible sag. Also, in view of the saving in weight of this type of cable, compared with other alternatives, it was possible to employ a simple single-screw fixing for the embracing-type cable hangers.

Mr. R. H. A. Reid (*at Newcastle upon Tyne*): In Table 6 there are 33 faults attributed to corrosion due to deterioration of paper fabric serving, and none due to damage to serving during installation. Are the authors sure of these figures, or could some of these faults not be due to small stones having got into the blinding during installation and been forced into the serving?

Table 6 also shows five cases of mechanical damage to underground cables during installation in a total of 52 faults, or 10%. Again, there are five faults due to extrusion defects, presumably due to gas blow holes. The fractures were found during installation, but is it not possible they might not be found then?

Mr. L. A. Bates (*at Newcastle upon Tyne*): The absence of any reference in Fig. 1 to the supply of aluminium-sheathed cables to the mining specification is noteworthy, and one wonders why so little progress has been made in this field, where the higher conductivity of the aluminium sheath should give it a considerable advantage over other types. It is perhaps too early to ask whether the authors have any useful information on the experimental installations which are referred to in Section 5.3.3.

With regard to the composition of the aluminium for sheathing, an analysis of a sample length (in 1949) showed this to be of a higher purity (99·87% aluminium) than that specified in B.S. 1471 for grade T1B metal. Is this of any significance in respect of its corrosion-resisting properties?

The authors clearly show, and my own limited experience with aluminium-sheathed cables confirms, the importance of providing outer coverings which can be depended upon to remain impervious to moisture for a very long time. Furthermore, it is essential that such coverings should be reasonably protected against mechanical damage, which is likely to cause trouble unless the outer tape is of really robust construction. When one considers also that armouring is more likely to be dispensed with in the case of the aluminium-sheathed cable with its superior mechanical strength, the design and performance of the outer coverings is of much greater importance than in the case of lead-covered cables. L.V. aluminium-sheathed cables with P_2C coverings have been in service underground for about 3 years in this area, laid in a heavy clay soil which generally is mildly alkaline. These cables have been examined at intervals at random points, and so far the amount of sheath corrosion has been small. Some slight corrosion is, however, taking place, even in what may be called favourable soil conditions, and this only serves to emphasize the need for a really dependable outer covering.

Mr. D. R. Parsons (*at Newcastle upon Tyne*): The company with which I am concerned has ¼ in coaxial cable, grade T1E, erected on some thousands of houses and, so far as I am aware, no trouble has yet been experienced.

The method of suspension that we have been using consists of a spiral wire catenary with a supporting wire of stainless steel. The suspension wire is polythene-covered copper and appears to have given very satisfactory results.

Mr. J. F. Gobbi (*at Liverpool*): The use of an unreinforced aluminium sheath is particularly attractive for high-voltage cables operating under internal gas or oil pressure. The authors however, conclude that to give adequate creep strength some work-hardening is necessary if sheaths of standardized thickness are to operate permanently at pressures of 250 lb/in^2. This conclusion is based on a 3% extension to break over a 35 year life. It is also based on the creep behaviour of a particular tube which apparently varies in grain size from 0·1 to 0·4 mm.

Tube extruded at a much lower temperature, on a press designed for direct cable sheathing, exhibits a more uniform and smaller grain size, averaging 0·03 mm. It is to be expected that the creep characteristics of such tube will be superior to those quoted in the paper and consequently no work-hardening will be required.

It may also be of interest to mention that the author's experience of weakness at stop-marks, attributed to a transition from coarse to fine grain structure, has not been experienced with the direct extrusion press quoted, where it is virtually impossible to detect any change of grain structure at the stop-mark.

In Section 4.3.3, reference is made to tests designed to ascertain the effect of relative movement of conductor and sheath. These tests were presumably on cables with aluminium conductors and aluminium sheaths. Whilst the behaviour of the single-core type of cable is more critical, the reason for choosing a large conductor cable is not clear. The relative movement would have been more pronounced with a smaller-conductor cable where the temperature differential between conductor and sheath is greater. Perhaps the authors could amplify details of the test and give the latest position.

A recent installation at Kemano, British Columbia, comprises two 3-phase circuits of 300 kV oil-filled single-core cable. Each circuit has the conventional copper-conductor lead-sheath

* Hollingsworth, P. M., and [Raine, P. A.: Paper No. 1638 S, April, 1954 (*see* 101, Part II, p. 603).

construction, resulting in a differential expansion per 2000 ft of installed cable on full load of 5 in. The cables for the second circuit have an aluminium conductor and aluminium sheath with a differential expansion of 6 in. The point of interest, however, is that, whereas in the first circuit the sheath tends to elongate with respect to its conductor, in the all-aluminium cable the conductor will tend to elongate with respect to the sheath. The latter is the more dangerous situation, particularly in view of the less yielding nature of an aluminium sheath.

This all-aluminium cable has another novel feature. The cable sheaths are supported on insulators, bonded and earthed at the centre of each circuit only. This is not normally convenient, but it eliminates the otherwise heavy sheath-circuit currents, which form the major part of the sheath losses referred to in the paper.

Mr. T. A. P. Colledge (*at Liverpool*): The General Post Office in this country use about 25000 tons of lead for about 3000 sheath-miles of cable per annum. To supplant this it would require about 6000 tons of aluminium per annum.

The great majority of cables used for telecommunication are drawn in in ducts laid in the ground, so that one of the chief aspects that have to be considered is that of corrosion due to contaminated water in the ducts. The authors have dealt with corrosion in some detail, and I would only add that the General Post Office are carrying out tests on the protection of the aluminium sheath with various coverings, including polythene. This additional covering, of course, increases the cost of the cable.

The experiments in progress cover both swaged and extruded aluminium-sheath cable. Some of these lengths have been laid bare and some are protected with polythene. It has been found that the swaged aluminium cable is stiff to handle, and the minimum radius of curvature must be large compared with a cable sheathed with lead if kinking is to be prevented. This means large-diameter cable drums, and care has to be taken in bending the cable round manholes, etc. The extruded sheath, however, is more ductile, and although it is not as easy to handle as lead-sheathed cable, it is quite acceptable. As the Post Office standard length of cable is only 176 yd, I imagine it should not be difficult to sheath a length of cable by the extrusion method in one continuous process. It would appear that the smooth-type cable can be used for easy bends, whereas the corrugated-type would be more suitable for the more difficult bends. Where cables have to cross bridges which are subject to vibration and stress due to bridge movement, aluminium-sheathed cable should prove better able to withstand such conditions. In addition, of course, the weight supported by the bridge will be considerably reduced. One such bridge where this type of cable could be used with advantage is the Conway Bridge, where we are limited to the weight of cables that can be supported by the bridge.

It is interesting to note the result of vibration tests that have been made on these cables. Underground cables which generally run along roads are subject to considerable vibration due to the traffic. This leads to creepage along the duct. Have the authors any knowledge of the behaviour of aluminium cables in this respect?

Finally, I would say a word about their cost. There appears to be little doubt that some sort of protection should be applied to the aluminium-sheathed cable for underground use. A polythene coating is being used at present and it naturally increases the cost of the cable. Another factor might be that the overall size of the cable will be increased, which means that a greater duct space would be required for the same number of circuits. In addition, the cable manufacturers will have to reimburse themselves for the cost of additional plant.

Mr. P. R. Dunn (*at Liverpool*): I am puzzled by the stress laid by one or two speakers on the difficulty of installing a cable without damaging the corrosion protection on which it depends for its existence. Quite apart from aluminium-sheathed cables, there is considerable experience of pressurized cables with steel reinforcements, where protection against corrosion and preservation of the integrity of the protective layers are no less vital than for aluminium-sheathed cables. The authors may care to give their opinion on whether there is any real difference in the protection problems involved. If there is not, then I submit that in the performance record of steel-reinforced pressurized cables there is evidence to allay the fears of the speakers referred to.

Mr. W. Holttum (*at Liverpool*): Can the authors state the maximum amount of strain per cycle which occurred in the sheath flexing tests referred to in Section 4.3.3(*a*)?

Mr. T. A. Maguire (*at Liverpool*): Mr. Colledge has referred to Post Office cables over Conway Bridge. We have cables in the same location, but having crossed the bridge they are not in ducts but are laid direct in ground which is saturated either with peaty effluent or with sea water. Have the authors had any experience of such conditions and their effects on aluminium sheathing? From our experience with overhead aluminium conductors (and particularly connections) in this area, we are very concerned as to what the effects would be on underground cable.

Mr. L. C. Grant (*at Liverpool*): I would like to ask whether the authors have had any experience of medium-voltage aluminium-sheathed paper cables laid in peaty ground. I have had two breakdowns in such situations.

I would also like to refer to the necessity for putting an impervious layer on the aluminium sheath. It reminds one of certain types of ground, met for instance in Cheshire, where in many districts one cannot lay steel pipes because of the inroads of the anaerobic microbe. Attempts have been made to get over this by coating with bitumen, but the slightest mechanical damage to the covering of the pipe such as would occur with a hobnail boot, for example, has been known to make a single puncture in the bitumen resulting in damage to the pipe. This risk can be reduced by wrapping the steel with woven glass fibre coated with a bituminous compound. There is a parallel to this in the plastic covering used for aluminium cables. Can one rely on a cable which has only a thin plastic covering which may be damaged? It may be stood upon or it may be badly used at bends and joints. This does seem to be a difficult point, because cables have to be laid under awkward conditions.

Mr. T. Makin (*at Liverpool*): Fig. 2 shows comparative costs of aluminium, lead and copper, but I think the value of the paper would be improved if comparative costs of the finished lead-covered steel-wire-armoured and aluminium-sheathed cables were included.

Since 1948 I have had experience in both underground and overground installations of aluminium-sheathed paper-insulated cables, and I have experienced cable failures in both. These were caused by deterioration of the sheathing due to hessian-pattern corrosion, as illustrated in Fig. 4(*a*).

In a cable with an improved type of protective covering, installed in 1951, a fault occurred due to damage to the covering during installation. The resulting exposed area of aluminium had corroded inside an earthenware duct with subsequent failure of the cable insulation.

With overground installations of bare aluminium-sheathed v.r.-insulated cables in dry situations, no trouble has occurred, but it has been noted that it is difficult to re-form a bend in such types of cable if route alterations are required.

I am pleased to learn that satisfactory protective coverings against moisture and soil attack have been developed, and I

hope that service conditions confirm the authors' stringent test results. I must stress, however, the importance of the utmost care in installation to avoid damage to protective sheaths.

Dr. J. L. Miller (*at Manchester*): The paper is an extremely thorough one and deals, often in considerable detail, with the problems of manufacture and utilization in a manner which I think should amply satisfy the cable engineer and cable operator. To some, I daresay, the fact that, as compared with lead-covered cables, there have been only a few years so far to obtain correlation between performance in the field and the results of the various accelerated life tests may be worrying. It appears to me, however, that there has been ample time for any real troubles arising from features, both design and operating, which had not been foreseen in the earlier testing stages, to be disclosed by now. To think otherwise, after the time that has already elapsed, would tend towards the reactionary and would not be in the best traditions of British engineering.

As is pointed out in the conclusions, aluminium-sheathed cables are an important addition to the resources of the cable industry; where it is economic they will no doubt be used. But where I think aluminium has distinct technical and economic advantages is in the two cases of oil-pressure and gas-pressure cables. Such cables have to carry heavy reinforcement, and the latter has to be heavily protected because its integrity is paramount—in fact there was a time when two lead sheaths were sometimes employed, the outer one protecting the reinforcement. The use of aluminium, however, obviates these difficulties and presents a neater solution to the problem. Also, some day, such cables might possibly break into the field at present held by the Oilostatic cable.

Then, too, on technical grounds alone, aluminium is eminently suitable for aerial cables, and where vibration is severe—in fact, in Germany, great lengths of coaxial telephone cable, aluminium sheathed, have been installed across the Rhine bridges.

In conclusion, I should like to refer to Section 3.1(*a*) by saying that an organization with which I am connected has in fact built a press which aims at continuously extruding sheath over cable using aluminium of commercial grade.

Mr. K. C. Coop (*at Manchester*): Our experience in the North West with aluminium-sheathed cables has been small, but it has served to indicate very clearly the rapidity with which corrosion can take place on the aluminium sheath in the presence of moisture. In view of this, I expected the paper to be considerably less definite in its conclusions, and I was therefore surprised to find such statements as, for example, the following:

> Manufacturing difficulties have been overcome.
> Solutions have been found to the problems of protection against corrosion.
> Servings incorporating overlapping p.v.c. tapes are satisfactory.

and all these within a period of six years.

Fig. 2 shows the trend of the base metal cost per cubic foot of copper, lead and aluminium over the years 1944–53. It would be very useful to have a realistic comparison of the cost of completed cables laid and jointed, taking into consideration the increased number of joints with the aluminium-sheathed cables and the additional cost for the protective servings.

In Section 4 it is implied that the bending test is merely a test of the sheath itself and has no relation to the cable as a whole. I should like to have some reassurance that the dielectric was not adversely affected by the corrugations.

Referring to Section 4.3.3, I should be interested to know what trouble the authors would expect with aluminium-sheathed cables plumbed to a circuit-breaker cable-box and restrained in movement within a 6 in-diameter pipe bent to the minimum allowable radius. I would imagine that the end thrust on the box might lead to a cracking of the wipe.

Turning now to the protection against corrosion, there is a significant paragraph in Section 2.4.3, where it is stated that one or other of the combinations of circumstances favouring corrosion of aluminium may be assumed to be present at some point of most underground cable installations, and the second statement in Section 5.1.2, that any form of substantially non-hygroscopic covering will protect aluminium from atmospheric attack; it is merely required that the material or combination of materials shall remain permanently intact.

I must reiterate that the important factor is the time element and although the authors are satisfied with the information obtained to date, that the servings incorporating overlapping p.v.c. tapes have eliminated the corrosion problem, there must still be a doubt in our minds as to what will happen to the sheath after a period of 10, 20 or 30 years.

Mr. E. L. Davey (*at Manchester*): It is clear from Section 3.2 that the defects which used to be present in cable lead-sheaths can be present in the aluminium pipe, and these defects may only appear in service. In particular, cable lengths are limited to single charge lengths of pipe in order to avoid some of these defects. The aluminium sheath and the joints have to be hermetically sealed to prevent corrosion, and this is an extra duty as compared with lead-sheathed cables in normal situations.

One might ask, then, what is the function of the aluminium sheath, since mechanical strength can be provided by an armour. The answer is that the anti-corrosion protective coverings are moisture-resisting but are permeable to gases and vapours including water vapour. An impregnated-paper dielectric under an anti-corrosion protective covering would absorb the permeating water vapour until electric failure occurred. In the case of the aluminium sheath or other metals under the coverings, no absorption of the water vapour occurs and a stable condition obtains.

Turning now to Section 4.4.3, in particular to Fig. 22, I would ask the authors to give more details regarding this test, especially as regards the pressure records. When a fully impregnated solid-type lead-sheathed cable terminated with compound-filled sealing ends is subjected to heating cycles, the pressure rises during the first cycle to a value of 70–120 lb/in^2 absolute, the exact value depending upon the distension pressure of the sheath. During subsequent cycles the pressure at the maximum temperature falls to a stable value of 50 lb/in^2 absolute as the sheath distension is completed, and at the cold temperatures the absolute pressure is of the order of 1 or 2 lb/in^2 absolute, due of course to the formation of voids in the distended sheath.

In the authors' case, according to the data given in Fig. 16 for aluminium sheaths, the pressure should reach 700 lb/in^2 approximately before sheath distension occurred, unless sufficient air or gas was initially incorporated within the cable to give the requisite cushioning or unless the sealing ends burst. The incorporation of gas spaces in the sealing ends would not be sufficient to prevent a high pressure rise on a long feeder.

If gas space is initially provided within the cable, the use of an elevated pressure is indicated. The pressure rise under temperature cycles is limited by the gas space provided, while the elevated pressure will increase the ionization stress, and as a corollary it follows that all the free compound in the dielectric should be removed and replaced with gas so that compound drainage is obviated. The idea of a solid-type aluminium-sheathed super-voltage cable seems to be totally illogical.

Dealing with the relative differential thermal expansion between the conductor and sheath, in 3-core cables a good deal of accommodation is obtained by the cores separating or closing up so that the pitch diameter of the cores alters.

In a single-core cable the excess thermal expansion of the conductor over the sheath can only be accommodated by

ıcrease in the pitch diameter of the layers of the stranded onductor. If this increase in the overall diameter of the onductor exceeds, say, 1%, the dielectric papers will be broken. Calculations show that this possibility exists, especially on ırge-conductor low-voltage, and hence thin dielectric, cables here the temperature difference between the conductor and ıeath is small.

By replacing a lead sheath with aluminium and replacing a opper conductor with aluminium, the expansion of the con-uctor relative to the sheath is increased to a value dependent on ıe relative temperature rises, since the materials are the same.

Mr. P. H. Leadbeater (*at Manchester*): We have installed in ıe local undertaking here about 6000 yd of aluminium-sheathed ables laid during 1948–49. This cable was served with the ormal compounded paper and hessian tapes which would have een used on a lead-covered cable, and of course they have given onsiderable trouble. With this experience, and also because amples were laid in the depot yard in various grades of soil, and nder carefully controlled conditions, the opinion has been ormed that none of this cable will still be in operation 20 years om now.

We also had some 3000 yd of cable which was in stock at the me when these troubles developed which the manufacturers ery generously re-served free of charge with the new p.v.c. and lass fibre tapes, and which has since been laid and has given no rouble to date.

The technique developed by the pioneers of this cable for aking plumbed-type joints on aluminium-sheathed cables ppears to be perfectly satisfactory. We have had no trouble at ll either during the installation or after.

We have also had some experience in the use of unserved luminium-sheathed cables for control purposes in a major ubstation. There were a large number of cables involved, all mall, the largest being about 1 in. Very considerable difficulty as experienced during the installation in handling even these mall cables, and even with more experience the labour costs of andling will undoubtedly always be much higher. Against his, the cost of supports can be much reduced, and also there is onsiderable financial advantage as against lead-covered bright-vire-armoured cables.

In conclusion, I should like to make a few remarks about luminium-sheathed cables in general. The first is regarding as-filled or impregnated pressure cables. I should like to put in a lea for the use of aluminium sheath for this purpose. There eems to be no possible objection, and a very considerable inancial advantage. In both instances the life of the cable is lecided by the life of the serving. The extrusion of a sufficiently tout p.v.c. sheath over the aluminium sheath seems to be very atisfactory, but I should like to see the p.v.c. extruded over a ituminous coating on the aluminium, so that if the p.v.c. should e damaged, water would be unable to pass between.

I should also like to have the authors' opinion on the possibility f extruding a very thin lead sheath over the aluminium sheath. rom the point of view of the consumers, this may not be as mpossible as it sounds, as we are quite sure that even a thin ayer of lead will give protection over long periods, but are we uite sure that accelerated ageing tests on p.v.c. prove that it ill remain satisfactory for 50 years to come?

Mr. H. G. Allen (*at Manchester*): My primary interest in ables is in their installation, and it seems to me that, after the able technicians have argued the merits and demerits of this ype of cable, the choice will still be largely economic. In this onnection, the difficulty of installing aluminium-sheathed cables ill offset to some extent the savings obtained in other ways.

These cables require more labour in installation than lead-heathed cables, particularly in power station work, or other situations where the cables are in air, and a considerable amount of adjustment is necessary to give the installation a workmanlike appearance.

Messrs. R. H. Stewart and **R. W. Newcombe** (*at Stone*): In certain applications the conductor area of copper-cored lead-sheathed cables does not depend on its normal continuous rating. Instead, it depends on its short-time rating under short-circuit conditions. From British published figures, this results in an extremely large core area, often ignored in practice on grounds of economy! Typical figures are quoted in Table A. This shows permissible currents for certain lengths of time and the appropriate basis. An illustrative practical example is also given with Table A. In such applications is it economically favourable to use either copper-cored aluminium-sheathed cable or aluminium-cored aluminium-sheathed cable?

Table A

SHORT-TIME RATING OF CABLES UNDER SHORT-CIRCUIT CONDITIONS

Time of current flow	Cable applicable to 6·6 kV, 11 kV and 33 kV paper-insulated cable		
	(*a*) 0·3 in²	(*b*) 0·2 in²	(*c*) 0·1 in²
sec	amp	amp	amp
0·2	50 000	34 000	17 000
0·5	32 000	21 000	10 000
1·0	23 000	15 000	7 000

(*a*) Based on maximum current to create temperature of 160° C in the conductor.

Example.—A transformer, fed by a 3-core armoured paper cable laid in a duct, takes a load of 90 amp from a 6·6 kV 250 MVA system. The transformer is protected by a standard inverse definite minimum time relay with definite minimum time setting of 1 sec. To carry the full-load current of 90 amp, a 0·04 in² cable capable of carrying 104 amp continuously would suffice. On short-circuit, however, the possible fault current would be 22 000 amp, and from Table A, col. (*a*), the cable capable of carrying this current for 1 sec is a 0·3 in² cable. The continuous rating of the 0·3 in² cable is 313 amp, which is 3 times the continuous rating of the cable required to carry the full-load current.

The authors advocate unprotected aluminium sheaths except in 'contaminated industrial atmospheres'. Surely this vague term needs further clarification. How does it apply to paper and steel mills, for which steel-wire-armoured p.v.c.-served cable is advocated?

Often lead-covered control cables are rejected owing to stripping of the lead reducing the insulation level between conductor and sheath. This is due to the lead biting into the insulation at the joints. Do aluminium-sheathed cables suffer this disadvantage?

Mr. H. McCartney (*at Stone*): It appears that the authors call for the use of aluminium as a sheathing material almost wholly as an alternative for lead. The use of lead is primarily to provide the insulation with a waterproof covering. Where, however, aluminium sheathing is to be used for buried cables, the authors consider that further waterproof coverings are necessary to protect the sheathing against corrosion. As metallic sheaths are essential, by regulation, only for high-voltage cables, and as non-metallic waterproof coverings are becoming available, it seems likely that there will be particular scope for the development of buried-type cables having no metal sheath.

Where a lead-sheathed power cable is within the protected zone of a quick-acting protection system and it fails owing to an internal fault, one expects visible evidence of the precise position of the fault, usually by a small hole burned through the sheath. It appears, however, more likely that where aluminium is

used the sheath exterior will be undamaged, mainly because of the higher melting-point and greater thermal conductivity of aluminium.

If unarmoured aluminium-sheathed cables were used in a mining subsidence area, would the authors agree that one might expect more fractured joint wipes than if armoured lead-covered cables had been used?

Mr. B. O. Ashford (*at Portsmouth*): Research organizations are at present making soil-corrosion tests, including bare specimens of aluminium sheathing material in various types of soil. Even if corrosion is observed to be negligible in certain cases, the findings would not detract in any way from the fundamental importance of the authors' statement that considerations of possible effects of oxygen deficiency prohibit altogether the use of bare aluminium underground.

Anxiety as to permanence of plumbed joints on aluminium-sheathed cable in ducts or in air, with joints not embedded solidly in bitumen, has been difficult to dispel owing to widely circulated statements from the United States describing rapid corrosion failures of such joints, accelerated apparently by thermal movement of the adjacent cables. Laboratory tests in which these conditions, chemical and mechanical, have been reproduced in their most onerous form have shown that a thin coating of bitumen, applied molten, is wholly effective in preventing interfacial corrosion, provided that the plumbing-metal/tin boundary is bitumen coated, including a margin of an inch or so on either side.

Referring to the alternative method of sheathing by continuous welding of formed strip and subsequent reduction by rolling-down, as distinct from cold-sinking, it has been established that the final D.P. hardness of the sheath is rarely more than 10% greater than that of the original annealed strip, permitting thinner sheaths (for equal bending performance) than those produced by the authors' process, in which 50% increase in hardness on cold-sinking would appear to be quite typical. The difference is accounted for in part by the fact that reduction by rolling (which incidentally involves no significant alteration in cross-sectional area) is performed on tube which is still hot from the welding process. The high thermal conductivity of aluminium ensures fairly even redistribution of welding heat in the short interval between welding and rolling.

The other process of reduction—corrugation by means of a rolled helical groove—results in a more flexible cable, at least equal to a lead-sheathed cable in respect of ease of manipulation in confined spaces.

Mr. T. G. C. Harrop (*at Portsmouth*): I should like some further explanation of the theory of the cause of corrosion of the aluminium sheaths when the cable is clipped close to a wall. Is the corrosion chemical? I do not see how a cable can become anodic to itself in such a short distance.

Has any experience been gained with aluminium-sheathed cables laid in the earth in areas where stray electric currents are liable to be found, e.g. in shipyards where a considerable amount of welding is taking place?

What do the authors think of the future prospects of aluminium-sheathed cables in merchant ships? The advantages in warships, where saving of weight is of great importance, are obvious.

Bearing in mind the precautions which are necessary on board ship when aluminium is used, however, and the fact that weight is not as vital in a merchant ship, I feel that although the cable will stand up to marine use, it will be ruled out on the score of economics.

Mr. A. G. Milne (*at Bristol*): On the score of price and availability, I do not think one needs to be a prophet to forecast that aluminium will be used for cables in increasing quantities in the years ahead. Indeed, digressing for a moment from the case of the aluminium sheath, we find it economic now to replace copper by aluminium in the cores of m.v. cables and on m.v. overhead lines. A recent investigation into the relative costs of lead-sheathed copper-cored and aluminium-cored m.v. cables in a fairly large housing site showed that there would be a saving by using the latter. With the aluminium sheath, the picture is not so encouraging. The three well-known troubles associated with aluminium sheathing are corrosion, efficiency of joints and handling difficulties. We would have to be convinced that corrosion troubles will not occur in the buried cable for the life of the cable. A protective covering of extruded p.v.c. should be reliable, although it would have to be of sufficient thickness to withstand damage during pulling and when laid. Lead sheathing has given such continuously excellent service that replacement by aluminium sheathing would have to show substantial advantages.

About five years ago we installed, as an experiment, aluminium-sheathed l.v. cables, and from time to time we examined the joints and the sheathing. Initially, we found the joints were faulty, but we accept that this was due to the jointers' inexperience in wiping; subsequent examinations have so far proved the joints to be satisfactory, but insufficient time has lapsed for us to draw conclusions. Cables are subject to movement, owing to vibration, subsidence, etc., and it is in these conditions that we should like to be assured that the joint will be satisfactory. Another difficulty is that the making of the joint requires more care than the lead joint. This is important because skilled labour is becoming scarce and consequently less reliance can be placed on the efficiency of the routine jointing of the aluminium-sheathed cable. For these reasons, and because of the handling difficulties in awkward cable runs and the relatively large number of service and main joints, we do not think that at present there is a case for aluminium sheathing for l.v. and m.v. cables.

Probably a better case can be made for very-high-voltage cables, especially the impregnated gas-pressure type. Here again, we recently investigated the economics of installing $0{\cdot}4\,in^2$ 33 kV solid separate lead-sheathed cable as compared with a $0{\cdot}3\,in^2$ impregnated gas-pressure aluminium-sheathed cable and whereas the capital cost of the latter was very much lower when the losses were taken into consideration and the total of the capital charges and annual losses were capitalized, there was very little difference. Having regard to the lower operating and maintenance costs of the solid cable, it ought to be the one that is chosen.

Mr. F. P. Phillips (*at Bristol*): What precautions are necessary when jointing aluminium cores and sheath to a conventional copper and lead cable? Also, what is the significance of the splaying of strands recommended when jointing aluminium cores?

Mr. D. J. Smith (*at Birmingham*): Could the authors state the highest voltage for which aluminium-sheathed cables have been installed in this country and abroad, and did they experience any difficulty with the gas-pressure type in drawing the three dielectric conductors into the aluminium sheathing?

I was interested in the photographs of various installations and noted in one case a number of aluminium-sheathed cables cleated closely together. This could, in certain conditions of humidity and high soot concentration, etc., give rise to trouble with corrosion. Can the authors say whether troubles have occurred at these points, and whether they can make any recommendations as to types of cleats and any precautions necessary?

I have installed this type of cable in public supply substations in this area, using single $7/{\cdot}65\,in^2$ varnished-cambric aluminium-sheathed cable on the m.v. side of a 1 000 kVA transformer, and $3/{\cdot}022\,5\,in^2$ varnished-cambric aluminium-sheathed cable

the 11 kV side. Some difficulty was experienced in the 11 kV switchgear terminations, but a satisfactory technique was evolved in conjunction with the switchgear manufacturers, and no troubles have occurred although these cables were installed over five years ago.

Much more difficulty was experienced in bending and setting the 0·65 in² cable, since considerable manual effort was required in the restricted space of a small substation, the length of cable involved being 8–10 yd. The problem was solved when a template was made and the cable preset before it was offered to the transformer.

Mr. P. M. Martin (*at Birmingham*): In Section 2.4.2 the authors say that the possibility of alkaline attack on aluminium is not considered serious. Strangely enough, although a test is made on cables embedded in cement, no mention is made at this stage of cables laid and supported in trenches, which must form a fairly common method of installation.

In Section 5.1.5, however, it is stated that there is a serious hazard in the use of bare aluminium, particularly when in contact with damp walls. This statement is also amply borne out by the fault analysis given in Table 5, which seems to be somewhat a contradiction to the remarks contained in Section 2.4.2. I should like more details of the types of failure which are included under the heading 'Faults resulting from proximity to damp walls'.

In 1949–50, I was responsible for the installation of a sizeable h.v. and l.v. works distribution system, and for reasons of cost, and also more particularly, of delivery, it was decided to utilize aluminium-sheathed cables. These were laid bare, without any serving, in concrete or brick trenches, the latter normally being dry, but it was not always possible to avoid damp conditions, and one of the trenches was accidentally flooded on two occasions. After three years' service the first of a series of faults developed, on a 7 kV 3-core cable forming part of a ring main, and thereafter faults occurred on this section with such monotonous regularity that it became necessary to replace the whole cable, and for this we reverted to lead-sheathed. All the faults that occurred on this length were due to penetration of the sheath, and in my view the cause of this corrosion was alkaline attack from the concrete of the trench where it was in contact with the cable. It may also be that during installation, when the cable was being dragged into the trench, small particles of concrete became embedded in the sheath, and they might have set up local areas of corrosion. I should be glad to have the authors' views on that possibility.

I have no doubt that with the experience gained since the days of our own installation, precautions can now be taken to eliminate these troubles completely; in fact, one of the authors has outlined what precautions should be taken. In this connection, I should like to know whether the cost of p.v.c. serving adds appreciably to the total cost of the cables, and whether they are still an economic proposition compared with lead cables. I should also like to have the authors' views on the installation generally of cables of this type in concrete or in brick ducts, and the method of supporting them.

Mr. J. H. Patterson (*at Birmingham*): I should like to enlarge on what Mr. Smith has said with regard to the installation of aluminium-sheathed cables in substations. I took a great interest in that project at the time and was able to connect up a large transformer by means of aluminium-sheathed cables on both h.v. and m.v. sides. The h.v. run consisted of three 0·0225 in² runs and the m.v. side consisted of three 0·6 in² and one 0·3 in². The 0·0225 in² cable presented no difficulty at all as regards bending to shape, but we had a very difficult job in bending the 0·6 in² runs. At that time, inquiries for a suitable bending tool elucidated the fact that there was no such instrument on the market. Eventually formers were made which in some respects eased the position, but before these were made the jointer was forced to sit on the floor with his feet braced against the transformer and two other men bent the cable round his body.

In the first operation the cable had to be constantly taken down and reset in order to conform with the run, with the result that it took much longer to erect and cost much more money than the lead-covered equivalent. This caused me great disappointment, since I felt certain that a tool could be produced whereby the cable could be erected without so many removals.

The sites selected were different; one was a situation where there was considerable atmospheric humidity, and the other was subject to considerable smoke and fumes from a manufacturing area. After all these years the aluminium shows no signs of deterioration in either case.

Will the authors state whether there is any difficulty in running a large cored cable where two right-angle bends have to be negotiated?

So far as lead-sheathed cable is concerned, even where the cross-section is large, no difficulty is experienced in pulling a long length round bends with the rollers suitably placed. I have always been rather alarmed at the fact that corrosion may take place on buried cable, and suggest that the protection of hessian service in itself is not sufficient.

Mr. H. J. Gibson (*at Birmingham*): Previous experience with aluminium, certainly in marine and overhead-line work, indicates two very serious failings—corrosion and metal flow. It is conceded that, when the surface is not in contact with other material and becomes oxidized, further corrosion is substantially prevented by the oxide film, but at points where there is any contact, particularly with metal, or in even slightly chemical atmospheres or near the coast, there is not anything like the same certainty. This may have particular significance when aluminium is used for underground cables.

In the Midlands we look forward to underground cables lasting some 100 years, and if aluminium-sheathed cables are going to shorten this anticipated life, we must discount their value accordingly. I was somewhat perturbed when one of the authors said that although he is a chemist he could not forecast what would happen to aluminium in any particular ground. I know, of course, that precautions have been taken to protect the aluminium sheath by wrapping it in rubber or plastic, or something of that nature, but how long is that going to last, and how can we be sure that it is going to last sufficiently long to give us the same service as lead-sheathed cable? If once the covering is damaged or pierced, I think the authors will agree that there is every chance of the aluminium corroding very rapidly and giving rise to cable failure.

I should like to ask the authors, therefore, whether they feel confident about the protection against corrosion, and whether they are satisfied that voids are not created by the flow of the sheath resulting from expansion. I ask the latter question because of unfortunate experience with cone-type joints on steel-cored aluminium conductors which failed, after relatively short periods of operation in some cases, owing to the aluminium 'flowing' and loosening the joint. The difficulty was overcome only by using extended wrapped joints, similar to Canadian practice, or better still, compression joints, which produce a homogeneous 'weld' between the ends of two lengths of cable owing to the ability the metal has to flow.

Mr. R. Paterson (*at Birmingham*): Others may be interested in the experience gained in a steelworks with about 12 miles of m.v. aluminium-sheathed cables, about half of which was installed by 1951. The cable sizes ranged from 7/·029 2-core v.r. to 0·3 in² paper-insulated, with jute or hessian serving, or two p.v.c. tapes plus one glass-fibre tape and one hessian tape, and all with copper conductors. The cable has been used as an overhead line

suspended from a steel catenary cable by canvas straps; also underground in a wide variety of soils and ash, but always bedded in quarry sand; also in steelworks buildings and substations; and sometimes bare aluminium-sheathed cables have been drawn into ducts, which may be wet, or laid on steel brackets in concrete trenches, in which case a strip of leatheroid has been placed between the bracket and the aluminium.

Experience has been favourable to date, and further installation is proceeding, but lead sheath with wire armour is still chosen where wet conditions are known to be particularly acid, and prejudice still favours lead sheath and wire armour, but the substantial capital savings with aluminium, up to 30%, are a strong influence in its favour.

The only breakdown to date was on a 7/·029 in multicore aluminium-sheathed and hessian-served cable in a corner where men had committeed a nuisance. The authors' advice and comments on what changes they would make to our practice would be welcome.

It would be interesting if we could have comparative cost figures for paper-insulated aluminium-sheathed cable and paper-insulated lead-covered steel-wire-armoured cable.

Mr. H. M. Fricke (*at Birmingham*): In the early part of the paper the authors refer to the spurs of scarcity and cost, which did so much to prompt the development of aluminium as a cable-sheathing material. World supplies of bauxite ore are very adequate for all foreseeable requirements of aluminium, while the availability of lead appears to be limited, and its present high cost is certainly a problem.

I can quote costs based on the present cost of raw materials, referring to the four types of cable specified in the early part of the paper, which show a saving of approximately 33% for aluminium-conductor aluminium-sheathed cable in the 0·2–0·3 in^2 range over copper-conductor lead-sheathed cable.

Mr. E. Bramald (*at Birmingham*): The authors have explained at great length the efforts made to prevent damage of the sheath should moisture or other corrosive materials be present, but it appears that there is nothing to prevent mechanical damage during installation.

Have any experiments been carried out in the way of covering the cores before sheathing with a waterproof membrane, such as Neoprene, before enclosing it in the aluminium? In this way the possible penetration of the aluminium might not be detrimental because of the underlying barrier of waterproof material.

Mr. E. C. Cooper (*at Birmingham*): We have recently heard reports of metal failure due to fatigue, especially in aluminium alloys. Moreover, I have recently read a report of a failure of a cable sheathed with pure lead due to fatigue cracking. The fatigue was apparently caused by vibration over a long period. Could the authors say whether there is any danger of aluminium sheaths cracking owing to fatigue?

Mr. T. D. G. Wintle (*at Birmingham*): I find the question of fatigue in the aluminium sheath raised by Mr. Cooper most interesting, because it is obvious that the smaller sizes of aluminium-sheathed cables could well be used for machine-tool work or something of that nature.

I wonder whether either the authors or Mr. Fricke have any comparative costs for aluminium-sheathed cables against conduit and v.r. cable.

Also, could the authors give some brief details of the method by which the sheath can be removed? I take it that it is somewhat similar to any lead sheathing, but I should like that confirmed. How do the cost and manipulation compare with mineral-filled cable?

Mr. H. S. Davidson (*at Birmingham*): The tube-sinking process described in the paper seems to suffer from one main disadvantage, in that the metal is hardened during the process, and this restricts the bending radii of the cables. In the direct-extrusion process the finished cable is much more ductile, and smaller bending radii can be achieved. This process is mentioned in the paper, where it is suggested that if certain difficulties are overcome it might become more general. The paper was prepared about two years ago, and I should like to ask the authors whether they can report any developments in the direct-extrusion process which might lead to its wider adoption in preference to the tube-sinking process.

Mr. E. W. A. Edmonds (*at Plymouth*): Is it possible to stop or retard corrosion once it has started on a cable sheath? I have a sample of severe hessian-pattern corrosion on a cable which has been laid four years in a clay soil near Falmouth.

Mr. W. E. Johnson (*at Plymouth*): Two lengths of aluminium cable were laid in my area in August, 1951, and up to the present time no trouble has appeared. From time to time, when work has been necessary on these cables, the bitumen has been removed from one or two joints made in 1951, and no trouble could be found either to cables or plumbs.

At the same time that these cables were laid, a short length was sealed with two pot ends and laid direct alongside the live cable; the joints on this test piece were not laid in bitumen but were covered direct with earth. I have brought it to the meeting for the authors to see, and I should be glad to hear their comments. Lime was present in the soil where this test was carried out.

Mr. H. C. O. Stanbury (*at Plymouth*): I should like to draw attention to Fig. 27. Will the cable suspenders not cause corrosion of the aluminium sheath at the points of suspension in the way the authors have described as having occurred where a piece of string or a copper band had been placed round the cable?

In the Plymouth telephone area, aerial cable with lead-antimony sheath is largely used by the Post Office, and they have considerable trouble owing to the suspension rings cutting into the sheath, partly, no doubt, as a result of vibration set up by wind pressure. I should be interested to have the authors' opinion as to whether aluminium-sheathed cables would suffer similarly, since I understand that aluminium motor-car bodies develop cracks owing to vibration setting up a crystalline formation in the aluminium.

In Cornwall the Post Office has a good deal of trouble due to corrosion of their underground lead-sheathed cables laid in earthenware pipes, and I should like to know whether aluminium-sheathed cables would be more or less likely to suffer from this trouble.

Messrs. P. M. Hollingsworth and P. A. Raine (*in reply*): In replying to this discussion we would first of all like to thank the contributors at the provincial meetings who have presented such a fair cross-section of opinion and experience. Although there was a certain inevitable overlapping in the discussions at the eight meetings, we have attempted to deal with contributions individually as far as possible. Two subjects were outstanding amongst closely related questions; first, the expectation of life in anti-corrosion coverings, and secondly, the stiffness of the aluminium sheath in relation to installation.

Messrs. Cooper, Gibson and other speakers have drawn attention to the vital importance of performance in protective coverings, since it is admitted that the life of the cable is entirely dependent in most circumstances upon this feature. There are many records of old cables recovered after 30 or 40 years' service with textile servings intact although deteriorated by decay. In p.v.c. we have a material which, in addition to being more robust than textile servings, is virtually unaffected by soil chemicals or soil bacteria. The evidence of its expanding use all over the world during the last 15 years is impressive, since unlike the earlier coverings its behaviour has been constant

observed and evaluated. We cannot say that it will last 100 years, because our experience of synthetic materials is short, but we are able to assert that its proved durability predicts a long life.

Messrs. Gobbi, Colledge, Leadbetter, Allen, D. J. Smith, Davidson and J. H. Patterson were concerned with installation difficulties due to stiffness of the aluminium sheath when compared with the more familiar lead sheath. This feature, which is often an advantage, since it renders the cable self-supporting, can be an undeniable drawback, particularly where large-diameter cables are concerned. It may be alleviated by the use of bending tools, but it is not claimed that aluminium-sheathed cables can be handled by precisely the same methods as lead-sheathed cables, or that they can as easily be installed on a tortuous route. The installations where aluminium shows to greatest advantage are those where the routes have been planned from prior experience involving allowance for generous bending radii and care in positioning of supporting points to utilize the increased rigidity to the utmost. Mr. Bryant, in addition to giving a striking example of how aluminium-sheathed cable will resist rough handling, quoted a case in which rigidity and light weight with a 0·15 in^2 4-core cable were turned to good advantage.

The information in Table 6, which Mr. Reid queries, was carefully compiled from data received about the various faults. There was no evidence in any of the 33 failures under paper-fabric coverings of stones having been forced into the servings, and we do definitely know that serving damage was not responsible for the faults. In some instances the cables had been laid in sifted sand. The possibility of faults due to extrusion defects has been very thoroughly investigated, and as a result the quality of present-day tube is very different from that obtainable in 1948. The sheath failures reported were early examples, and none has arisen since.

As Mr. Bates points out, the amount of cable manufactured to mining specifications was too small to be recorded separately in Fig. 1. Despite the advantages of higher conductivity and also light weight and strength (for shaft cables), mining engineers are reluctant to use aluminium sheaths, first because of fear of corrosion or difficulties at joints, and, more recently, because of alleged risk of sparking. The fact that aluminium-sheathed cables are furnished with efficient protective coverings and steel armour which are taken right into joint boxes disposes of these objections, and we see no reason to avoid using aluminium-sheathed cables in mines. There is no further information to report on the experimental cables referred to in the paper, which are expected to operate free from incident (barring accidents) for many years. From the aspect of corrosion resistance, the use of metal of higher purity than grade T1B has no advantage for cable sheathing. Grade T1B has adequate corrosion resistance for exposure in air, and efficient protection would be essential for use underground irrespective of the purity of the metal.

We were interested to learn from Mr. Parsons that the continuous-spiral method of support from a catenary wire has been found satisfactory for an aluminium-sheathed cable.

Mr. Gobbi has drawn attention to the value of aluminium sheaths for the retention of high internal pressures, but does not agree that some work-hardening is always desirable for this application. The introduction of a modified extrusion technique resulting in more uniform grain size may, as he suggests, increase creep strength so that work-hardening for gas-pressure cable sheaths becomes unnecessary, and we await the practical results of tests with interest. Equally, methods of direct extrusion on to cable core which avoid work-hardening or change in grain size at stop-marks will undoubtedly contribute to improved bending performance in finished cable. Mr. Davidson was also very interested in direct extrusion, but unfortunately we are not yet able to say that all production problems concerned in the process have been solved.

We have nothing specific to report on the behaviour of single-core aluminium-conductor aluminium-sheathed cable. Tests are in progress, and no ill-effects due to differential expansion have yet been observed. The choice of a large conductor for these tests was made, bearing in mind the greater possibility of damage to insulation if differential expansion occurred in such an instance. We have no information on the behaviour of the Kemano cables referred to, but agree the distinction as to the different conditions which could prevail due to expansion. The elimination of sheath current by single-point earthing and cross-bonding using insulated joints is normal practice in North America, and could, we think, be considered with advantage for similar installations here.

Mr. Colledge gave us an interesting résumé of Post Office requirements for the sheaths of telephone cables, where the necessity for cables to be accommodated in existing ducts and manholes does not really favour aluminium. All aluminium sheaths for such situations must be externally protected, and this requirement often prohibits their use on the grounds of increase both in size and cost. He has, however, shown that such considerations may often be waived when lightness and resistance to vibration in a sheath are a first consideration, as they are on bridge structures.

Mr. Holltum will be interested to learn that the maximum amount of strain in the flexing tests was 0·15%.

We are grateful to Mr. Dunn for pointing out that there is no difference between the quality of protection required for an aluminium sheath and that required for the steel reinforcement normally used on lead-sheathed pressure cables; the reliable service experienced with the latter is undoubtedly reassuring for the former. There is one reservation, in that pressure cables, being h.v. feeders, are usually carefully handled during installation. This does not necessarily apply to all aluminium-sheathed cable, so that there may sometimes be greater risks of damage to servings.

Messrs. Maguire, Grant and Makin have rightly expressed concern at such risks, but the data on fault incidence given in the paper indicate that they are not very serious with reasonably robust coverings. Nevertheless, it must be conceded that damage to servings on a buried l.v. cable can have more serious consequences if the cable is unarmoured aluminium than if it is armoured lead.

We welcome Dr. Miller's remarks regarding the justification of using aluminium-sheathed cables on the basis of records of service over the past six years. We consider that the knowledge and experience now available are fully adequate to ensure reliable operation. This particularly applies to pressure cables, for which the advantages of aluminium are paramount, as Dr. Miller emphasized.

We consider that the evidence given in the paper amply justifies the statements questioned by Mr. Coop. As regards comparative prices, figures for specific sizes of cable can be supplied, but it is difficult to generalize. We can confirm that no damage to the insulation is sustained under the bending test as given in B.S. 480, Part 2. With suitable restraining measures, confining a cable bent in a 6 in pipe would not be expected to give rise to trouble, for assuming that the pipe referred to were of steel the effect of differential expansion would be to cause it to 'snake' in the pipe. Mr. Coop's assumption regarding the information in Tables 5 and 6 is correct.

We thank Mr. Davey for drawing attention to the primary reason for use of a hermetic sheath on cables having hygroscopic insulation, namely as a complete seal against moisture, for which

purpose no plastic material can replace metal. He asked about pressure conditions in aluminium-sheathed cable under load whilst undergoing stability test. The maximum pressures did not exceed 200 lb/in², since sheath clearances and therefore the initial air volume incorporated in the cable were about the same as for a similar lead-sheathed cable. Absence of sheath distension at the pressures reached no doubt assisted in the satisfactory performance of the cable in question, but we agree with Mr. Davey that the aluminium sheath shows to greatest advantage with high gas pressures, and think it strange that he has not so far considered it in relation to the gas-filled cable. While admitting that behaviour of large single-aluminium-conductor aluminium-sheathed cables under thermal expansion has not yet been fully explored, we do not altogether share Mr. Davey's fears about rupture of paper tapes. We suspect that, even with copper conductors, longitudinal expansion is sometimes restricted by the manner in which the cable has been installed, but have no knowledge of trouble due to damaged papers ever having occurred.

We are grateful to Mr. Leadbetter for his résumé of experience with aluminium sheaths and plumbed joints, and to the North Western Electricity Board for their co-operation in making this experience possible. Since the meeting where his remarks were made, various cables to which he referred, served with p.v.c. tape, glass and hessian, have been partially excavated and examined. In no case was there any sign of sheath corrosion. Practical considerations and economics apart, we can see no advantage in covering an aluminium sheath with lead, for although the risk of corrosion is thereby somewhat reduced, it is by no means eliminated. P.V.C. is a much more suitable material for this purpose.

Messrs. Steward and Newcombe have asked about the effect that short-circuit current ratings have on conductor sizes, a subject rather outside the scope of the present discussion. Our recommendations based on a maximum conductor temperature of 130° C for the conductor size required in the example quoted are 0·25 in² copper conductor; alternatively 0·40 in² aluminium conductor. In both cases full advantage has been taken of the fact that the temperature rise on full continuous load is much less than the maximum permitted value. With the aluminium conductor there is a further reduction in size due to the 15% advantage in heat capacity per unit length. Under short-circuit conditions the mechanical strength and high conductivity of an aluminium sheath are advantageous in reducing both mechanical and thermal effects. We have not encountered the phenomena they mention of 'knurling in' on metal sheaths, which may be peculiar to a certain type of joint. We can assure them that the mechanical joint illustrated in Fig. 24 does not produce any ill-effects on the cable. An all-embracing definition of 'contaminated industrial atmospheres' is difficult to provide, but one possible description is 'an atmosphere that promotes severe and rapid rusting of iron'. Steelworks are in that category and also certain parts of paper mills.

Mr. McCartney looks forward to the day when, by the use of non-hygroscopic plastic materials for insulation, metallic sheaths will be no longer necessary. We agree with him that under conditions of ground subsidence an unarmoured aluminium-sheathed cable could transmit severe tension on to a joint wipe, there being no armour to share the load. Such conditions have not so far arisen in service underground, but experience with an aerial cable under heavy tension due to extreme cold has shown that wiped joints do not fail readily and are in fact comparable in strength to the sheath.

We were pleased to have Mr. Ashford's support in refuting statements from United States sources which challenged the integrity of wiped joints. The reports in question appear to have arisen from observations on violently accelerated corrosion tests which have no counterpart in service. They do not affect the validity of the claim that no joint failures due to corrosion have occurred in service. Assuming that the quality of welding can be guaranteed at all times, the manufacture of cable sheath by seam welding is a notable contribution to cable-making technique, and when followed by corrugation it undoubtedly confers improved flexibility. It is interesting to note that the hardness of the sheath after the rolling process is not increased by more than 10%. An average figure for the sunk sheath is 25%.

Mr. Harrop, together with several others, has asked for more information on the mechanism of 'wall corrosion'. Unfortunately, space does not permit of detailed explanation, but the following may be helpful: There is nothing unusual in one part of a metal surface becoming anodic with respect to an adjacent part of the same surface; in fact, such a condition is one of the most familiar promoters of corrosion that is known. Frequent reference is made to the condition in Section 2.4, and it is readily brought about on aluminium by differential aeration of the surface. When a cable sheath is pressed against a wall, the portion with the oxide film in contact with the wall has a very restricted supply of oxygen, while the much larger adjacent areas are in free air. If some supply of electrolyte is now provided this small portion will become slightly anodic with respect to the remainder, the protective oxide film will be stripped, and the exposed metal being distinctly anodic to the more oxygenated portions of sheath which have the film still intact, will corrode rapidly. A damp wall readily provides a source of electrolyte in the concentration on its surface by evaporation of the salts carried there by moisture in the wall. Such corrosion can occur in the absence of any alkali or acid, but in common with all instances of crevice corrosion, chlorides provide intense stimulation. Hazards due to stray currents in the ground are countered by use of servings having an impervious layer. The variety of installation and operating conditions found on merchant ships would entail corrosion proofing as a standard feature which is economically unattractive except where strength and light weight are important.

Mr. Milne has underlined our observations on the future of this development being dictated by economics. In regard to the quality of wiped joints, we can assure him that they have shown themselves equal to all conditions so far encountered, including severe tensile and vibration stresses.

In reply to Mr. Phillips, the jointing of aluminium-sheath and lead-sheath cable is effected by the normal wiping procedure using tinned copper or lead sleeves. For jointing of aluminium conductors we would refer Mr. Phillips to information leaflets on the subject which are available from manufacturers.

Replying to Mr. D. J. Smith, about 75 miles of 33 kV aluminium-sheathed pressure cable has been or is being installed in this country and abroad. The highest-voltage cable so far used in this country is at 132 kV, and abroad (in Canada) there are installations at 69 kV, 150 kV and 300 kV. No difficulties are experienced in introducing gas-pressure-type insulation (0·10 in thick) into the aluminium tube. We have not found and would not expect that cleating cables in bunched formation gives rise to corrosion troubles in certain industrial situations where otherwise they would not occur. In fact, in industrial atmospheres close proximity to another cable or to any other non-hygroscopic surface often reduces the risk of corrosion. It was of interest to learn that Mr. Smith quickly evolved a solution when confronted with a problem of difficult bends.

Mr. Martin has drawn particular attention to the hazard of wall corrosion; corrosion of cables in contact with damp concrete trenches would fall in the same category. As previously explained the effect is not directly due to alkaline attack, and any embedded

articles of concrete would only play a minor role in the corrosion mechanism. There is little to choose in cost, on present metal prices, between unarmoured p.v.c.-served aluminium-sheathed cable and armoured lead-sheathed cable. Methods of installation are similar for both types, subject to ensuring that the serving of the former is not damaged during installation. The United States has followed this country and Canada in the development of aluminium-sheathed cables to a minor extent only. They are now being produced by at least one company, but principally for communication rather than for power systems. In addition to his comments on installation, to which reference has been made earlier, Mr. J. H. Patterson has provided interesting confirmation of the ability of aluminium to withstand moist atmospheric conditions, and, of course, we agree that impregnated hessian is not to be relied upon as a corrosion-resistant serving.

We can assure Mr. Gibson that the phenomenon of metal flow at conductor joints held under compression is not experienced on cable sheaths.

Mr. R. Patterson has outlined the advantages of aluminium-sheathed cable for overhead catenary work, and of the other methods of installation described, that of supporting in ventilated trenches not subject to flooding is also suitable for bare cable. Nevertheless, where more than one method of installation is involved, including ducts or trenches which may become water-logged, protective coverings are essential and an extruded p.v.c. sheath, or alternatively p.v.c. tape with braided finish, would be suitable. The question of comparative costs has been answered as far as possible in these days of changing metal values by Mr. Fricke's contribution, for which we are indebted to him.

The suggestion of Mr. Bramald that a 'waterproof membrane' of Neoprene be enclosed within the sheath is not really practicable. It would add greatly to size and cost, apart from which, being only relatively impermeable, it would not, as explained earlier, be capable of excluding moisture permanently.

Both Mr. Cooper and Mr. Wintle were interested in fatigue resistance. In this respect an aluminium sheath is incomparably better than any lead alloy, and is finding increasing application on plant and structures subject to vibration.

We cannot quote comparative costs against conduit systems, since conditions of installation influence the figures so considerably, but it can be said that aluminium-sheathed cable is usually competitive. This relationship applies also to copper-sheathed mineral-insulated cable, the manipulation of which is very similar. Stripping of the sheath is effected as for a lead cable, and for the small sizes can be done with a small knife.

The samples of cable which had been buried by Mr. Edmonds and Mr. Johnson both showed a little corrosion after four years' interment, but none was evident at the wiped joints, which had not been protected in any way. In so far as buried cable is concerned, it is unlikely that corrosion once initiated will become self-arresting, although this certainly does occur on sheaths exposed to the atmosphere. An experiment has been in progress for some years to test the possibility of inhibiting corrosion by cathodic protection; this will be reported in due course.

In reply to Mr. Stanbury, we would point out that the cable in Fig. 27 was supported by aluminium cleats, and for each cleat the crevice was filled with an inhibitive paste. Even without this precaution, since the cable is not exposed to marine atmospheric conditions, risks of crevice corrosion are negligible. We have no fear of mechanical damage to the sheath due to the cleats. The cracking in motor-car bodies referred to by Mr. Stanbury is undoubtedly due to stress corrosion of the particular alloy employed, and the pure aluminium used for cable sheathing is not susceptible to failure of this kind. It is possible that the unusually severe corrosion of lead cable in earthenware pipes was due to stray-current electrolysis, which could be prevented only by protective coverings, irrespective of whether the sheaths were lead or aluminium.

DISCUSSION ON
'A CRITERION OF DISTRIBUTION COSTS'*

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 9TH JANUARY, 1956

Mr. W. A. Carne: There are so many factors involved that a straightforward comparison between Area Boards is more likely to be misleading than informative. The author recognizes the many variations between Boards and endeavours to allow for these in his calculations; in doing so he has produced a document that could be said to comply completely with the best definition that I know of statistics, i.e. 'a method of proceeding by a complicated mathematical process from an unwarranted assumption to a foregone conclusion'. The unwarranted assumption in this case is that the commercial efficiency of distribution of Boards varies sufficiently widely to enable the reasons for the variations to be established by a method of comparison.

It is a fact that all Boards contain a mixture of many former undertakings, that distribution practice has been common throughout the country and that the boundaries between Boards are in many cases arbitrary geographical lines. All this leads to the suggestion that, so far as distribution commercial efficiency is concerned, the probability is that all Boards are equal but some are more equal than others. The Boards within the latter category are London, South West Scotland and South Wales—each of which has major peculiarities that render comparison with other Boards virtually impossible.

Fig. 1 shows that a straight line could be drawn through the points representing the four southern Boards that are adjacent in territory and similar in development, and also another line for the five adjacent north of England Boards. These two lines seem to be eminently reasonable and represent for the southern Boards a capital cost of £10million fixed plus £50 per kilowatt and for the northern Boards a cost of £5million fixed plus £42 per kilowatt.

The suggestion that the Boards fall into two groups is also, I think, the conclusion reached by the author in Section 4.2, as shown in Table 5 and Fig. 3.

The differences in commercial efficiency revealed by the author's methods suggest that the source of the differences is more likely to lie in imperfections in his compensating adjustments for area and consumers than in any fundamental differences in economy of operating methods. The author to some extent recognizes this shortcoming when comparing Boards, but suggests that the discrepancy figures for a Board in successive years will be a guide as to whether the Board is doing better or worse. This again assumes that the compensating factors used in arriving at the discrepancy are correct; any inaccuracy would cause a drift in the discrepancy figure as the Board developed. The average rate of growth of Boards is, say, 10% per annum, and in three years a Board would have grown in some aspects by 30%; this might well produce a significant change in the discrepancy figure, owing to imperfections in the compensating factors for area, etc.

Mr. R. A. Hore: Statistical fitting of curves, or regression analysis, comprises fitting the curve and determining the statistical significance of the correlation. The fact that there is statistical correlation between two variables does not mean that there is a causal relation between the two. But if one knows that there is a causal relationship (i.e. one has additional information) one may then use the most probable value of the parameter evi though the data are insufficient to determine it very accurately In Section 2 the author has formally rejected regression analysis The method apparently used (fitting by eye) amounts, howeve to the same thing, save that it is more difficult, more laborio and less accurate. In fact, it has led him to draw erroneo conclusions—a not uncommon result of dealing with statistic data by non-statistical methods. I have applied regress analysis to find the coefficients a and b in the equation (Section 2. $y = ax_1 + bx_2$, and find that $a = £4{\cdot}1$ per kilowatt a $b = £46{\cdot}9$ per consumer.

The result confirms Schiller's suggestion and is in agreeme with Copland's paper* and discussion. Figs. P and Q sh

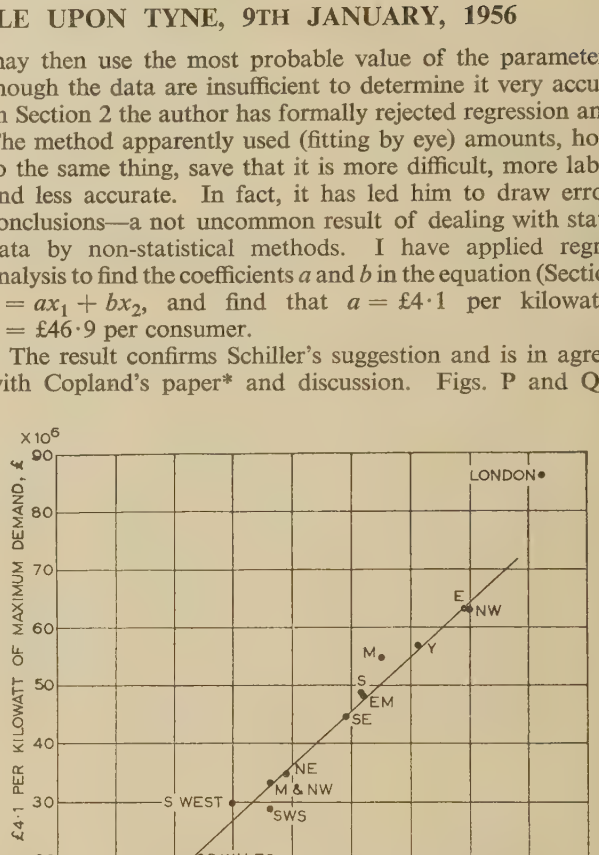


Fig. P

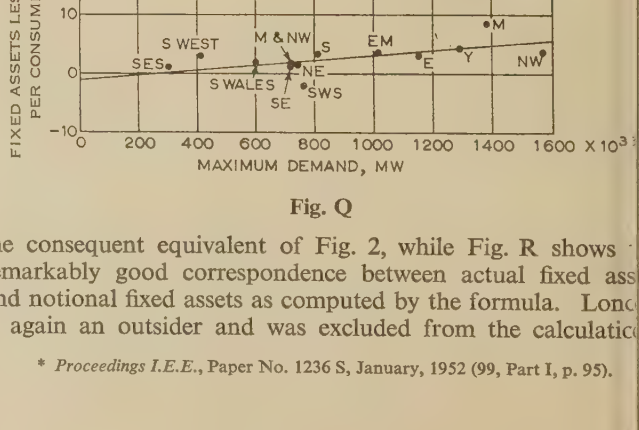


Fig. Q

the consequent equivalent of Fig. 2, while Fig. R shows remarkably good correspondence between actual fixed ass and notional fixed assets as computed by the formula. Lond is again an outsider and was excluded from the calculatio

* BOLTON, D. J.: Paper No. 1739 S, December, 1954 (see 102 A, p. 436).

* *Proceedings I.E.E.*, Paper No. 1236 S, January, 1952 (99, Part I, p. 95).

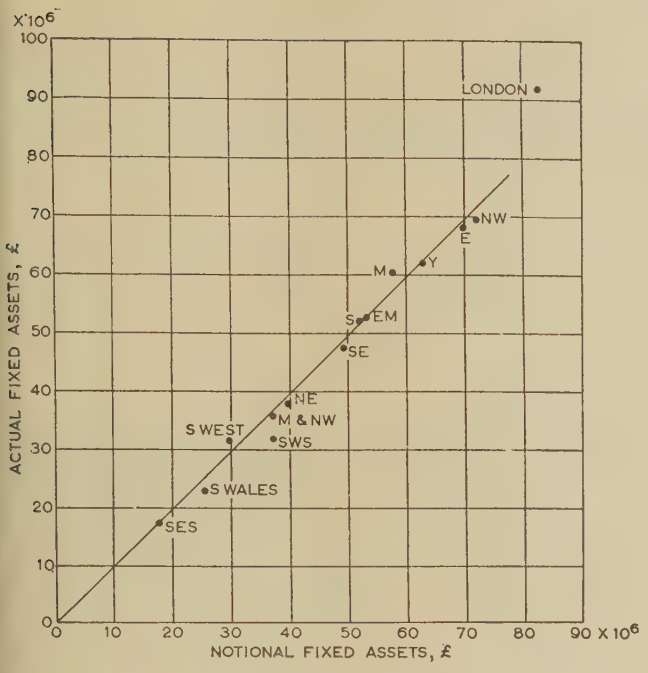


Fig. R

The calculations also show that the additional accuracy obtained by inclusion of a demand-related component, once a consumer-related component is taken account of, is not statistically significant, although it has been included on causal grounds. The regression plane passes almost exactly through the origin, providing confirmation of the author's supposition that there are no 'common costs' in the fixed assets.

It will be appreciated that the foregoing results affect not only matters raised in the paper, but tariffs as well.

The author's reasons for rejecting regression analysis are erroneous; 13 is an adequate number, and although x_1 and x_2 tend to vary together, resulting in somewhat ill-conditioned normal equations, with care and discretion acceptable results can be obtained and these are the best obtainable from the data by any method.

It also follows that unless we know of a definite causal relationship we should not include correlations which are not statistically significant. I cannot see any clear causal relationship between cost and area and certainly no justification for the choice of so complex a relationship as the fourth root; I consider therefore that this factor should be omitted.

I take it that the purpose of this criterion is to provide a measure of the efficiency of the various Boards. If due account is taken of everything the Boards do, the costs for all Boards should be the same (analytical errors apart). The object would therefore be defeated. I suggest, therefore, that only consumer requirements (or services) should be included, e.g. demand, consumption, security of supply. The resulting discrepancies, which—statistically—would be regarded as uncertainties in the coefficients or prices per consumer requirement, can be regarded in two ways: either as genuine variations in prices per consumer requirement for each Board or as variations in efficiency of the Boards. It seems to me that these two amount to the same thing, but that unless real reasons can be found for the former the Boards should not be damned or praised for the latter. One such reason which has been suggested is the ratio of clerical to engineering staff, and before adopting remedial measures one should make quite sure that the increased cost is not the result of a genuinely better consumer service (and thus, possibly, justifiable).

Does the author consider he has included all relevant factors? If so, why does he not suggest reasons or remedial measures in the south; if not, what further factors does he suggest should be included?

Mr. D. J. Bolton (*in reply*): As Mr. Carne says, it is, of course, possible that all 14 Boards are so nearly alike in the efficiency of their operations that the difference between them is unmeasurable. Such a result would arise only if they were all virtually perfect, in which case there would be no point either in comparing them or in plotting their yearly changes. This seems to me a far more 'unwarranted assumption' than the contrary one which Mr. Carne condemns. The fact that each Board is composed of some 30–50 pre-vesting undertakings is no reason why some Boards should not prove to be more successful in the economy of their operations than others, or to have made greater relative progress. The fact is that there *are* substantial differences which can be measured in the way described. The results are remarkably uniform for all changes in weighting within the range proposed by any of its critics, and the annual changes, even over four years' figures, are regular and consistent. Mr. Carne's suggested formula for asset investment of £10 million plus £50 per kilowatt is defective, because it provides only for differences in the kilowatts, whereas it is clear that additional consumers add to the investment apart from any increase in demand. His initial assumption that all Boards must be approximately equal in efficiency because they are averages leads inevitably to the final conclusion that if a measurement shows them not to be equal, this must be due to imperfections in the measurement.

Mr. Hore insists on his regression analysis and, like a mother with a sick child, likes it all the better when it gives an unacceptable result (approximately £4 per kilowatt and £47 per consumer). Moreover, he finds that the inclusion of a demand-related component is not statistically significant. This is the diametrical opposite of Mr. Carne's conclusion. Results which range as widely as from £50 to £4 (or zero) per kilowatt, and from zero to £47 per consumer, only confirm my own experience that, with the two components of the capital investment varying in the same direction and with every Board having substantial quantities of both, it is impossible to separate them mathematically with only 13 sets of data. A preferable method is that used as a check in the paper, namely by allocating the different classes of asset.

Replying to his last paragraphs: of course, if everything was allowed for all the results would be the same. I have tried to compensate for all the technical variations which can legitimately be expected to affect the cost of supply; what is left is presumed to lie within the Board's capacity to alter or improve. I do not agree that genuine variations in prices per consumer requirement are the same as variations in efficiency of the Boards. The former can be compensated for, either by my suggested technique or by some improvement thereon. When this has been so refined as to cope precisely with all the genuine variations there will still be something left, and this is what we want to find. What to do when we have found it (Mr. Hore's last question) would make another paper.

DISCUSSION ON

'PROVING THE PERFORMANCE OF CIRCUIT-BREAKERS, WITH PARTICULAR REFERENCE TO THOSE OF LARGE BREAKING CAPACITY'*

AND

'A NEW TESTING STATION FOR HIGH-POWER CIRCUIT-BREAKERS'†

Before the NORTH STAFFORDSHIRE SUB-CENTRE *at* STAFFORD 28*th October, the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM 14*th November, and the* NORTHERN IRELAND CENTRE *at* BELFAST 13*th December*, 1955.

Mr. S. M. Gonek (*at Stafford*): Tests show that it is possible for an air-blast circuit-breaker to interrupt a short-circuit current satisfactorily at a certain voltage and a single natural frequency but fail under similar conditions if the voltage is reduced and the natural frequency raised to maintain the same nominal r.r.r.v. evaluated in accordance with A.S.T.A. interim rules. This implies that the method suggested by the A.S.T.A. for the evaluation of a single-frequency, equivalent to a multi-frequency, transient may prove to be inadequate in future.

Has the satisfactory experience, mentioned in Section 3.2.3 of the paper by Messrs. Christie, Leyburn and Bird, been due to the fact that, in most cases, the circuit-breakers have been designed and tested at equivalent natural frequencies corresponding to two or three times the r.r.r.v. shown for the maximum fault MVA in Fig. 5?

Do the authors consider that, in view of the above, the proposed r.r.r.v. standards specified in Table 1 are inadequate and that the method for the evaluation of the equivalent r.r.r.v. in the case of the multi-frequency transients should be modified to cater for this characteristic, e.g. by specifying a transient enveloping the maximum instantaneous voltages which could probably be approached closer by tests at reduced voltages and suitable single natural frequencies?

Mr. T. J. Rowlands (*at Stafford*): Section 4.11 of the paper by Messrs. Christie, Leyburn and Bird makes the suggestion that a 5% test should be included in the test specification, and in order to preserve the objective of testing under realistic conditions, it is conceded that a certain amount of reactance should be placed on the load side of the circuit-breaker. A test of this type is included in Table 3.

The proportion of reactance on the load side of the circuit-breaker for the 5% test is given as 80%, whereas, in fact, 95% would appear to be the correct value to employ. What is the origin of the 80% reactance suggested? If a test of this form is considered necessary at 5% of the fault MVA rating, why is it not considered necessary at 10%, 30% and 60%.

Would the authors amplify their reasons for believing that large circuit-breakers are not often affected by the positioning of the test-circuit reactance, and would they indicate how the likelihood of trouble may be diagnosed without conducting tests?

Is it not possible that realistic siting of the fault-limiting reactance in tests on single-break air-break circuit-breakers would dispense with the 10% test with connections reversed, and that additional tests at 30% and 60% conducted in the same way would be likely to expose insulation weaknesses in the presence of ionized gas?

Mr. J. S. Cliff (*at Birmingham*): The proposals put forward by Messrs. Christie, Leyburn and Bird are very much in line with the tests which have been made during recent years at the major A.S.T.A. testing stations, and therefore they call for very little comment.

One of the additional tests which is increasing in importance is the auto-reclose test, particularly for export contracts where high-speed auto-reclosing duty is often specified for the higher voltage circuit-breakers. In this test, particularly with oil circuit-breakers, the second operation is much more onerous than the first, and to prove the circuit-breaker completely it is most important that the voltage and current should be as near to 100% as possible. The authors ask for some tolerance on the second operation, probably because of the characteristics of their testing station. On a test plant provided with super-excitation, it is possible to control the severity of the second operation, and even at high powers make it more onerous than the first if necessary. When unit-testing a half-pole of 132 kV 5000 MVA circuit-breaker on single phase, I have recorded the following values:

	Break operation		Make-break operation
Applied voltage	100%	15 cycles dead time	102%
Current	100%		110%
Recovery voltage	90%		94%

Such tests approach service conditions very closely, and illustrate the benefits of super-excitation.

Another aspect of circuit-breaker testing which has increased in importance recently is the ability to handle line-charging currents adequately, as mentioned by Messrs. Christie, Leyburn and Bird in Section 5.4. I agree that tests made with lumped capacitor banks are not easy to compare with the performance on actual lines, where the constants are distributed; and therefore tests on actual lines are preferable. The testing station with which I am associated is very fortunately placed, since three 132 kV circuits run almost over it. By agreement with C.E.G.B. headquarters, and with the co-operation of the local engineers, we have been able to make a connection to one of the circuits. During specified week-ends in the summer, up to 112 miles of 3-phase 132 kV line have been made available. By connecting the three phases in parallel, the equivalent of 250 miles can be obtained. The line is charged to full voltage from the test-station generators, through step-up transformers and the test circuit-breaker. The circuit-breaker is then opened, and the current and voltage variations are measured on the recording equipment in the testing station. These tests have already provided very useful data on both standard and experimental arc-control devices.

For the design of a new testing station there exists at present a considerable amount of data and experience accumulated in the various testing stations which have been in operation during the last 20 years. This information is freely exchanged among testing engineers, and Messrs. Christie, Leyburn and Fenn have undoubtedly availed themselves of the opportunity to study existing practice. It is therefore surprising that, in spite of the large size of the station, the outputs achieved are not relatively

* CHRISTIE, J., LEYBURN, H., and BIRD, J. F.: Paper No. 1707 S, August, 1954 (see 102 A, p. 697).

† CHRISTIE, J., LEYBURN, H., and FENN, R. W.: Paper No. 1736 S, December, 1954 (see 102 A, p. 709).

greater than those that can be obtained from stations using much simpler equipment. In the London discussion I commented on the relative merits of over- and super-excitation, and the comparative outputs at generator voltage. As the authors state, it is at the higher voltages where the maximum possible output is most useful. In the high-voltage range the comparison with a station equipped with super-excitation* is as follows:

Authors' three generators with over-excitation plus 15 transformers

3-phase	1 500/2 000 MVA
1-phase	1 600 MVA

Two generators with super-excitation plus nine transformers

3-phase	1 750 MVA
1-phase	1 500 MVA

(The latter value corresponds to an increase of 15% on the normal applied voltage, obtained by the super-excitation. Even more could be obtained in special cases.)

As the d.c. generators which form the super-exciters are much less costly than alternators, and the combination of super-exciter and correctly-designed alternator is much more flexible than an alternator with only over-excitation, super-excitation is now being used in most modern testing stations.

Mr. P. M. Martin (*at Birmingham*): I was particularly impressed by the actual contact of the making switches, which, for the duty involved, seemed to be very small. Could the authors give more information about these contacts?

Mr. R. A. J. Skermer (*at Birmingham*): What type of prime mover is used, and what steps are taken to compensate for the heavy sudden testing load, which would tend to stall the generator? Is some form of heavy flywheel fitted on the prime mover of the generator?

Mr. S. Taylor (*at Birmingham*): The authors state that valuable information may be obtained from scale-model tests in research and development. When we consider that the mechanical scale of the model must be suitably aligned with the electrical scale of the test circuit and with the scale of the performance of the model during the test, it is difficult to avoid the conclusion that the final interpretation of the test results must be open to considerable doubt.

Would the authors enlarge upon this aspect of synthetic testing, and also state to what degree they have been able to place reliance upon the extrapolated results from model tests when designing full-scale circuit-breakers? In this connection, I would expect particular difficulty with oil circuit-breakers having arc-control devices of the self-generated blast type, and would like the authors' views on this.

Mr. H. C. Fox (*at Birmingham*): It would be interesting to know whether super-excitation is used at the testing station at Arnhem.

Mr. J. S. Woodhouse (*at Birmingham*): Bearing in mind that the special 132 kV facilities available at the Birmingham station appear to be in some respects comparable to those available at the Fontenay Testing Centre, would it not be desirable in the interest of economy and co-operation to send some circuit-breakers to the Birmingham station instead of the French one?

Mr. W. J. Wright (*at Belfast*): In view of the present tendency to back circuit-breakers of inadequate rupturing capacity in low-voltage switchboards with high-rupturing-capacity fuses, I should be glad to know whether the authors consider this to be good practice, and if so, what steps should be taken before fitting the fuses in order to ensure that the circuit will be adequately protected under short-circuit conditions?

Where a l.v. switchboard comprises two main circuit-breakers for controlling the incoming supplies and several circuit-breakers controlling outgoing circuits, it is sometimes considered that the rupturing capacity of the circuit-breakers controlling the outgoing circuits may be less than that of the main circuit-breakers. Do the authors subscribe to this opinion, or should all circuit-breakers in a composite l.v. switchboard have the same rupturing capacity?

Mr. W. Szwander (*at Belfast*): A supply engineer, who has had the opportunity of watching at close quarters the working of switchgear testing stations, without doubt has his confidence considerably strengthened in the safety of the circuit-breakers installed in his system and in their ability to withstand satisfactorily the demands imposed on them by operating conditions in modern power systems. In this connection, no doubt the supply industry as a whole owes much to the leading switchgear manufacturers in this country for their achievements in the field of switchgear testing and for their willingness to immobilize considerable capital resources in the necessary facilities for that testing. Nevertheless it must be presumed that the cost of research and testing work is ultimately borne by the purchasers of switchgear, the prices of which must to some extent reflect the expenditure on testing. Hence the user of switchgear is interested not only in the highest possible quality of testing, but also in its lowest possible cost. While the relative values of field testing, of testing in high-power testing stations and of synthetic testing are appreciated, it is regretted that the authors have rather easily dismissed, at least in these two papers, the synthetic method of testing, which would appear to be the most economical. Since this method is used in some countries by manufacturers of the highest repute, it is difficult to believe that it deserves complete condemnation. It would be most instructive if the authors could give a brief review of the circuit-breaker testing methods actually used, and of the facilities available (with indication of maximum MVA) in the United States, Germany, Switzerland, Sweden and France, as compared with Great Britain. For example, how will the 330 kV 25 000 MVA circuit-breakers* of the Ohio Valley Electrical Corporation be proved? While the trend to ever-growing MVA fault levels in modern power systems is well established, much can be achieved by thoughtful system design to ensure at least a saturating character of this growth—hence the maximum rupturing capacities which may be required for circuit-breakers in various voltage classes should not considerably exceed in the future the values now envisaged. The present lack of clearly defined testing requirements and procedures concerning the breaking of magnetizing and of line-charging currents makes it very difficult for a prospective user of a circuit-breaker to establish its suitability for working in a particular system. The method, referred to by the authors, of checking a circuit-breaker against the known characteristics of a similar circuit-breaker which has been tested in conditions adequately simulating actual anticipated working conditions will not be regarded by the majority of switchgear users as sufficiently convincing. It is to be hoped that more precise testing rules will be introduced before too long. In Section 4.11 of the paper by Messrs. Christie, Leyburn and Bird, the statement that '. . . when a fault current of low magnitude is to be cleared, the bulk of the reactance usually lies between the circuit-breaker and the fault' is rather misleading. Quite obviously, in the most usual case of clearing a small fault current, the magnitude of the latter will be reduced by the small amount of generating plant in service, and hence by the reactance between the circuit-breaker and the sources of power.

Mr. D. S. Parry (*at Belfast*): The papers very clearly illustrate the considerable and diverse nature of the tests required to

* CLIFF, J. S.: 'Apparatus used in High-Power Switchgear Testing', *Journal I.E.E.*, 1937, 80, p. 593.
CLIFF, J. S.: 'Twenty Years of Progress in High-Power Switchgear Testing', *G.E.C. Journal*, April, 1955, p. 22.

* C.I.G.R.É., Paris, 1954, Paper No. 407.

prove the various types of circuit-breaker and the highly expensive equipment required for these tests. The papers indicate that a responsible manufacturer, having testing facilities available, conducts investigations into circuit-breaker performance far in excess of the requirements of the current British Standard. However, such thorough testing may conceivably be reflected in the price of the switchgear.

I believe that most of the trouble experienced on switchgear can generally be attributed to failure of components, and it would be most interesting if the authors could give some details about routine testing as distinct from type testing of circuit-breakers. I consider this to be most necessary in order to ensure that equipment supplied to the customer is of the same standard of workmanship as that tested, for proving the performance of the design.

Brief reference has been made in Section 6.2 of the paper by Messrs. Christie, Leyburn and Bird to field testing and its associated limitations, and then in Section 7.7 it is stated that testing-station tests and field tests are complementary rather than alternative. Would the authors enlarge upon the amount of useful information to be obtained from field tests?

In Section 4.8 of the paper by Messrs. Christie, Leyburn and Fenn, the authors deal with auto-reclosing duties, quoting minimum dead periods of 10–15 cycles. How does this time compare with that required for the circuit-breaker to clear the fault? In some circumstances a fault might not be cleared during the dead period, with consequent re-establishment of the arc. I am interested more particularly in voltages of 33 and 110 kV.

I believe that the short-circuit testing station has now been in operation for about two years. Have tests at the higher powers now available been made frequently during this period, and if so how has the plant stood up under such severe conditions, and what maintenance has been required upon equipment being continually subjected to short-circuit stresses, since plant in normal service would generally escape such onerous duties?

Messrs. J. Christie, H. Leyburn, J. F. Bird, and **R. W. Fenn** (*in reply*): We have found it most convenient to reply under separate subject headings, stating the names of the contributors immediately following each heading.

R.R.R.V. (Mr. Gonek).—The performance of a circuit-breaker may be affected by the growth of a restriking transient either in the initial or at a later stage. The A.S.T.A. interim rules, which take cognisance of both these effects, are therefore a reasonable compromise for assessing the severity of a multi-frequency transient. We do not consider that the problem raised by the speaker is sufficiently serious to warrant a revision of the rules or an increase in the proposed standard r.r.r.v. values shown in Table 1, particularly as the latter have been based upon severe system conditions.

Test Circuit (Messrs. Rowlands and Szwander).—Short-circuit currents of the order of 5% are usually due to a distant fault, and the placing of the bulk of the reactance on the side remote from the source represents that condition. The value of the 'remote' reactance depends upon the system conditions at the time of the fault, and 80% is considered to be a reasonable practical value.

Although the same considerations apply to other short-circuit currents, they are less important at the higher values because the ratio of 'remote' reactance to source reactance decreases as the current increases. For that reason a similar test at 10%, 30% and 60% is not considered necessary.

Super-Excitation (Messrs. Cliff and Fox).—Service conditions do not demand that the second break of an auto-reclose duty should be in excess of 100% of the circuit-breaker rating, and the values quoted by Mr. Cliff are therefore of academic interest only. In a testing station without super-excitation it is possible, in the example quoted by Mr. Cliff, to obtain, say, 95% of the rating on the second break by making the first break-test at, say, 105%.

Super-excitation is provided in the testing station at Arnhem but not in the most recent station built in the United States.

Testing-Station Output (Mr. Cliff).—It was not our intention to compare the outputs of testing stations. We cannot reconcile the single-phase output of 1 500 MVA quoted by Mr. Cliff with the output of 1 100–1 150 MVA which he has quoted in a previous description of the same station.* We presume that the lower outputs are obtained at standard voltages, which we consider is the only proper basis of comparison.

Line Switching (Messrs. Cliff and Woodhouse).—The facility provided by the C.E.A. for switching a 132 kV line will no doubt prove to be useful. With the corresponding facilities provided at Fontenay it is possible to switch longer lines over a wider range of voltages and with few restrictions as regards availability.

Making Switch (Mr. Martin).—The making-switch contacts for each pole consist of 16 butt contacts making at high pressure on to a flat moving plate.

Prime Mover (Mr. Skermer).—Each generator is driven by an electric motor, the power for the test being supplied by the mechanical inertia of the generator rotor which weighs 23 tons and runs at a speed of 3 000 r.p.m.

Synthetic and Small-Scale Testing (Messrs. Szwander and Taylor).—Small-scale and synthetic tests are used for research purposes, but are not sufficiently reliable for proving purposes. The tests are often arranged to reproduce phenomena observed in full-scale tests in order to investigate them more fully, but the final results should, in all cases, be confirmed by full-scale tests.

Assuming that synthetic tests suitable for proving purposes could be developed, they would have to be carried out at powers corresponding to a large percentage of the rating of the circuit-breakers. The cost of the testing equipment for this purpose, including the auxiliary apparatus, would probably be comparable with the cost of equipment used for direct testing.

Synthetic testing schemes and facilities available in other countries were carefully considered before embarking upon the building of the new testing station, but a full discussion of these matters would be outside the scope of the papers.

Excessive MVA in L.V. Network (Mr. Wright).—There is no objection to the use of a high-breaking-capacity fuse to back up a low-voltage circuit-breaker, provided that the combination is tested as a complete unit to ensure that its performance is satisfactory over the whole range of fault conditions.

On the other hand, the use of circuit-breakers on outgoing circuits with inadequate breaking capacity, interlocked with a fully-rated incoming circuit-breaker in order to ensure that the latter trips first under fault conditions, has not found favour in practice.

Routine Testing (Mr. Parry).—Adequate routine testing of circuit-breakers is essential if a high standard of performance is to be maintained. Such tests include mechanical and chemical tests of the materials, pressure tests, measurements of contact pressures and no-load operations of the completed circuit-breaker.

Operation of Testing Station (Mr. Parry).—During the two years that the station has been in commission some 5 000 short circuits have been made. The equipment has required little maintenance beyond the normal routine work undertaken on alternate week-ends.

* Cliff, J. S.: 'Twenty Years of Progress in High-Power Switchgear Testing', *G.E.C. Journal*, April, 1955, p. 22.

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

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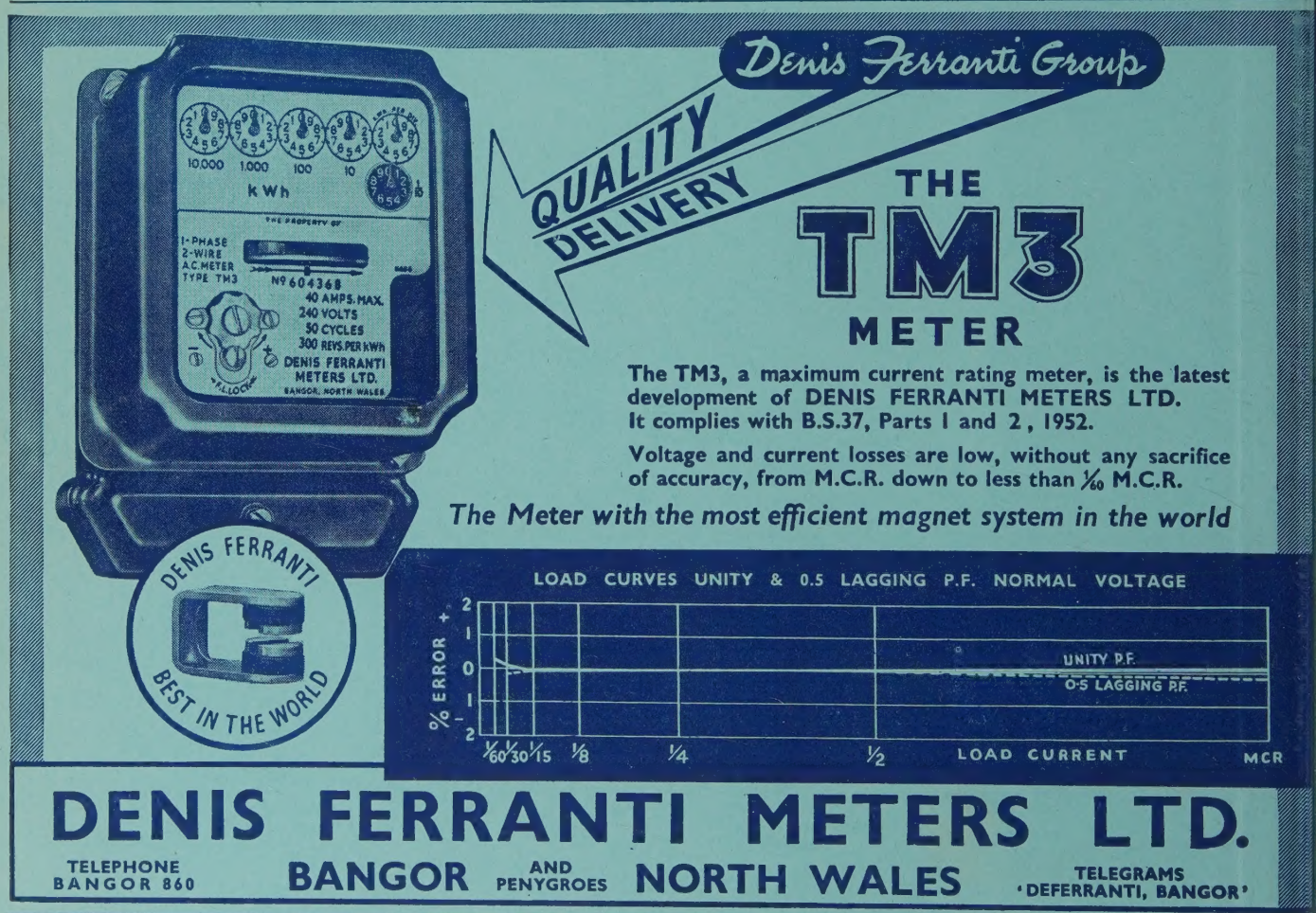
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